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Baran

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(54) **REAL CROSS TRAFFIC—QUICK LOOKS**

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(51) **Int. Cl.**

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H04N 7/18	(2006.01)
H04N 5/232	(2006.01)
G06T 3/40	(2006.01)
B60R 1/00	(2006.01)
B60R 11/04	(2006.01)
G06T 3/00	(2006.01)

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

CPC ***H04N 5/23238*** (2013.01); ***B60R 1/00*** (2013.01); ***B60R 11/04*** (2013.01); ***G06T 3/0018*** (2013.01); ***G06T 3/4038*** (2013.01); ***H04N 5/23216*** (2013.01); ***H04N 7/183*** (2013.01); *B60R 2300/605* (2013.01); *B60R 2300/802* (2013.01); *B60R 2300/8046* (2013.01); *G06T 2207/10024* (2013.01); *G06T 2207/20092* (2013.01); *G06T 2207/30252* (2013.01)

(58) **Field of Classification Search**

None

See application file for complete search history.

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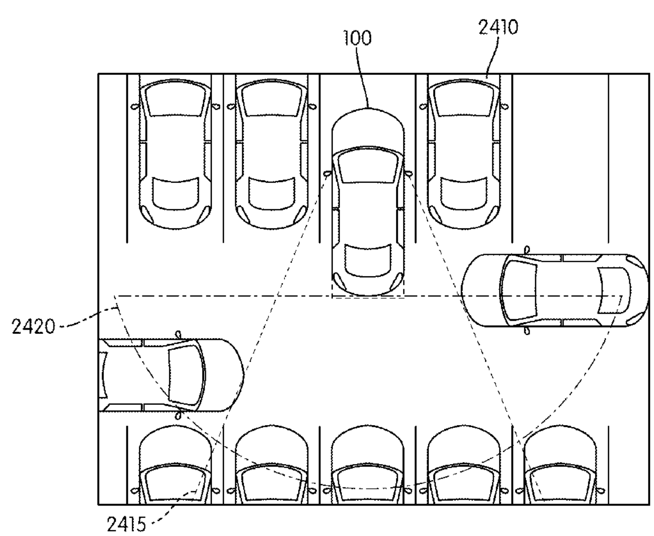
(74) *Attorney, Agent, or Firm* — Michael Best & Friedrich LLP

(57) **ABSTRACT**

System and method of performing various transformations between an omnidirectional image model and a rectilinear image model for use in vehicle imaging systems. In particular, a panel transform system and method for transforming an omnidirectional image from an omnidirectional camera positioned on a vehicle to a rectilinear image. The rectilinear image is then displayed to the driver for use while performing vehicle maneuvers. The panel transform system and method also provide a rectilinear image model based on the omnidirectional camera for use with existing rectilinear imaging processing systems. The rectilinear image model is determined based on a variable set of input parameters that are defined by both automatic and manual system inputs such as a steering wheel angle sensor and a user interface.

17 Claims, 13 Drawing Sheets



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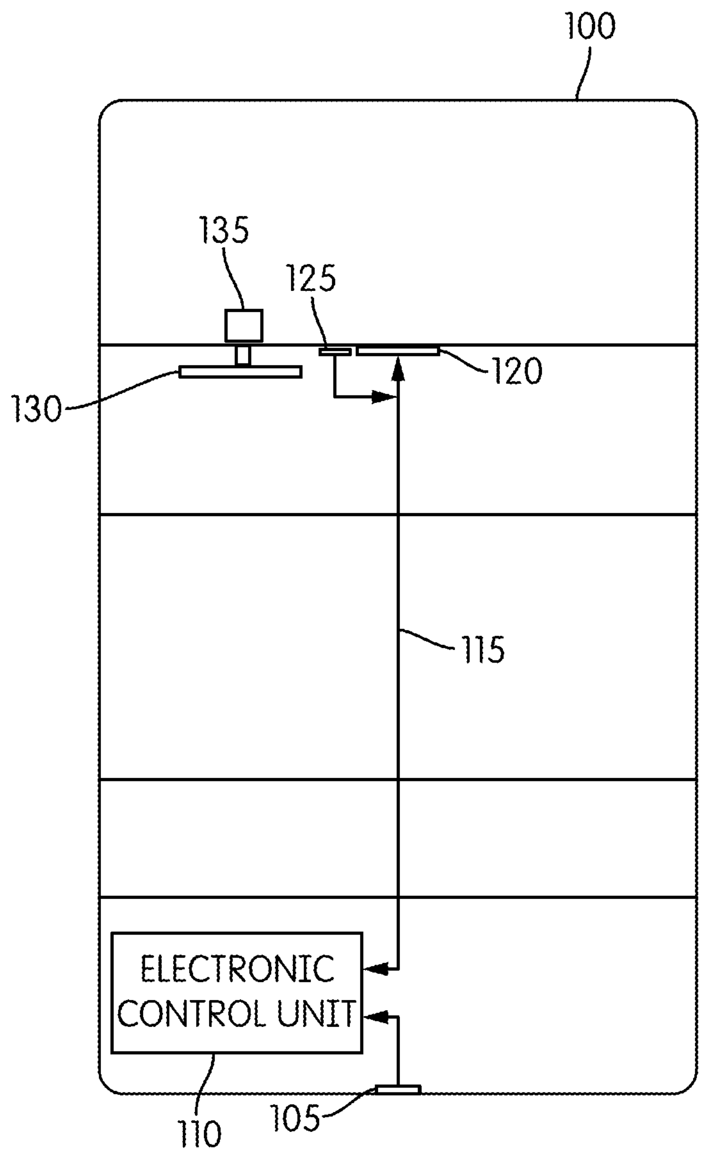


FIG. 1

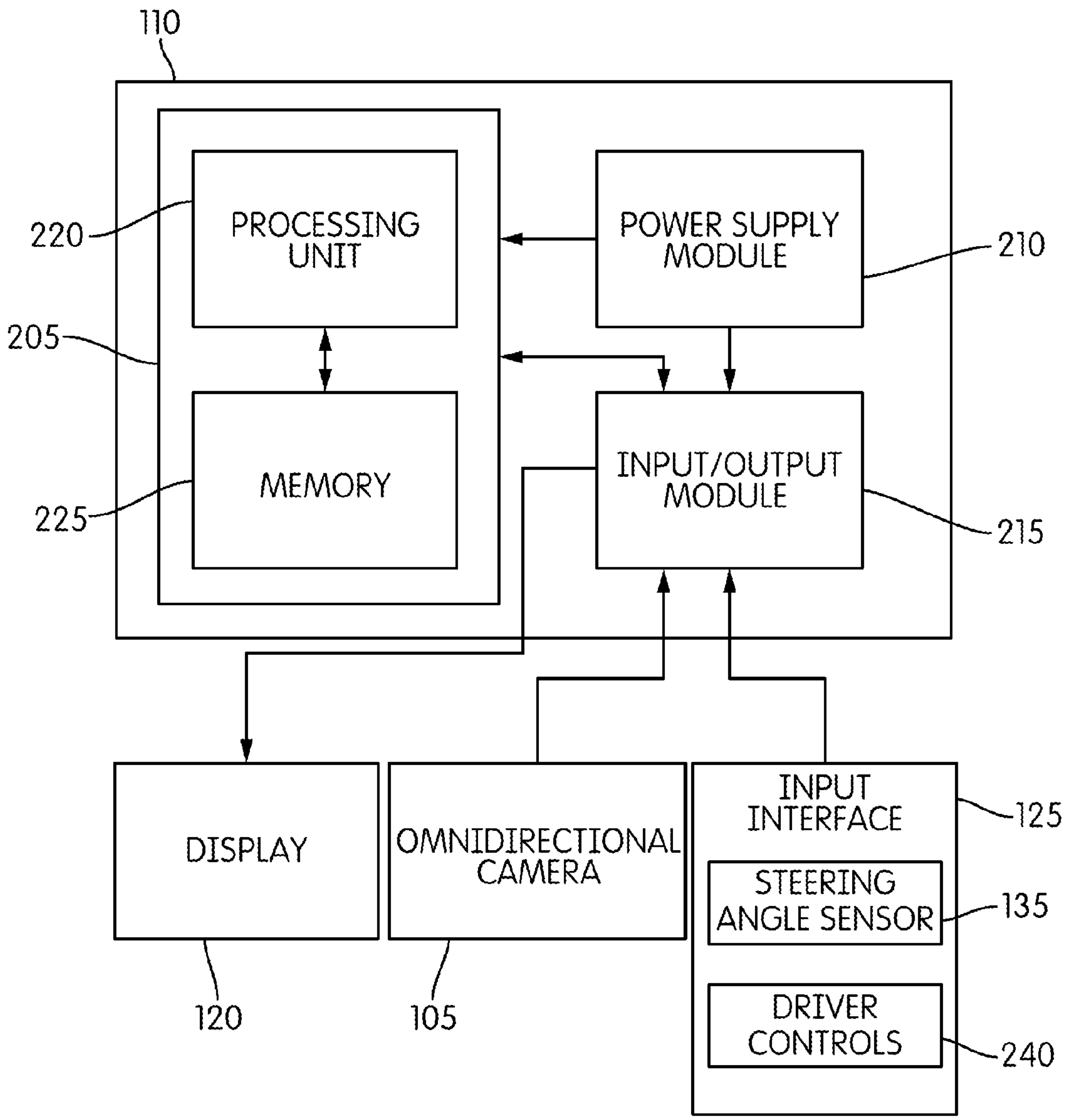

110
PROCESSING UNIT
POWER SUPPLY MODULE
220
205
210
MEMORY
INPUT/OUTPUT MODULE
225
215
DISPLAY
OMNIDIRECTIONAL CAMERA
INPUT INTERFACE
STEERING ANGLE SENSOR
DRIVER CONTROLS
125
135
240
120
105

FIG. 2

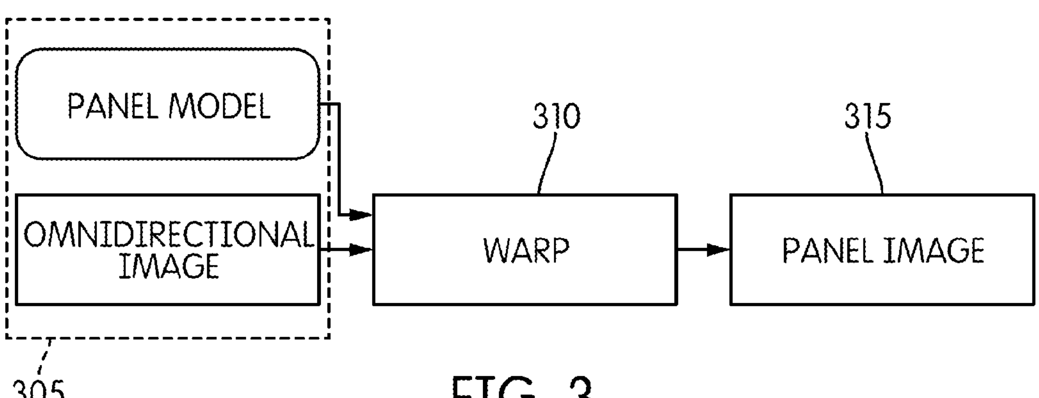

PANEL MODEL
OMNIDIRECTIONAL IMAGE
310
WARP
315
PANEL IMAGE
305

FIG. 3

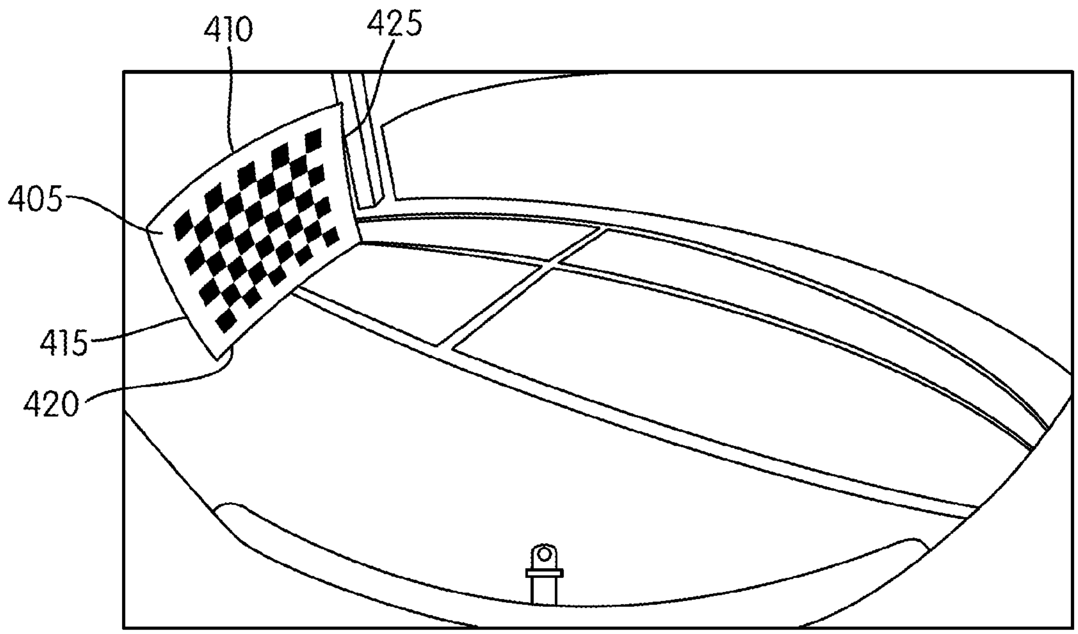


FIG. 4

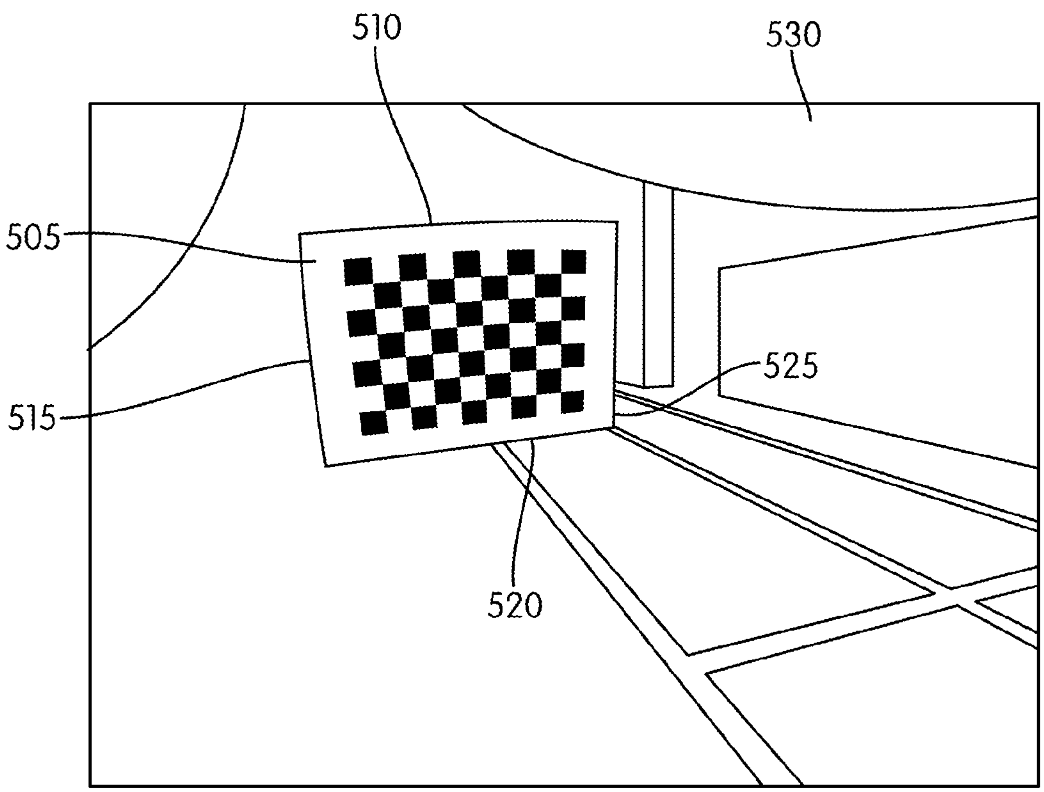


FIG. 5

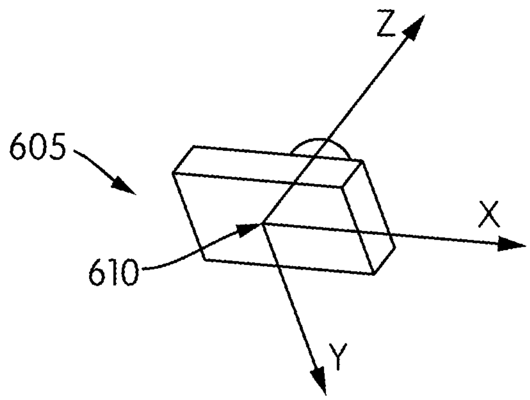

Z
605
X
610
Y

FIG. 6

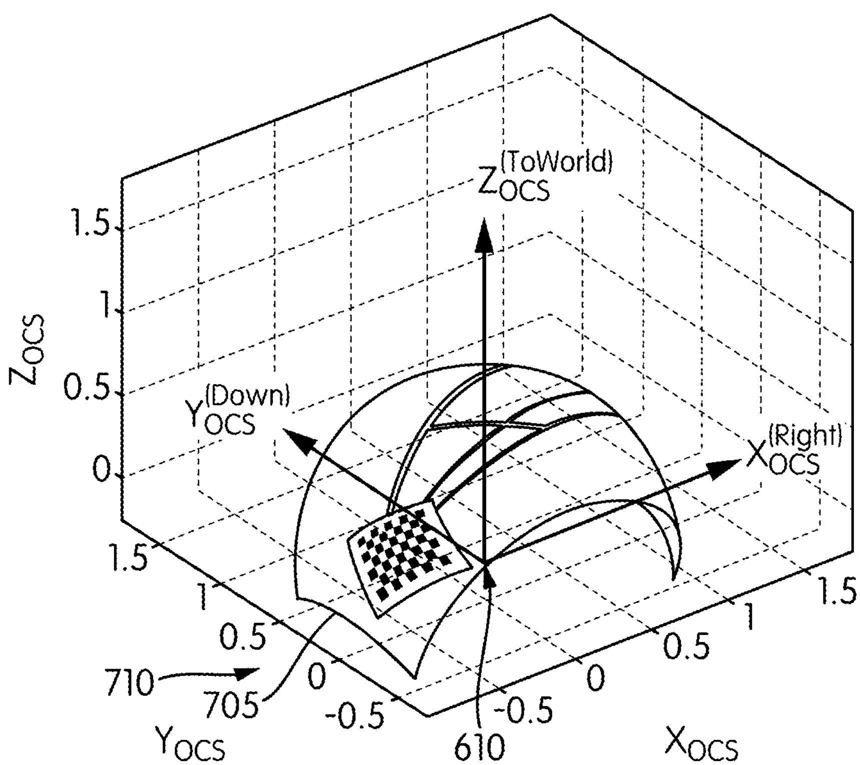
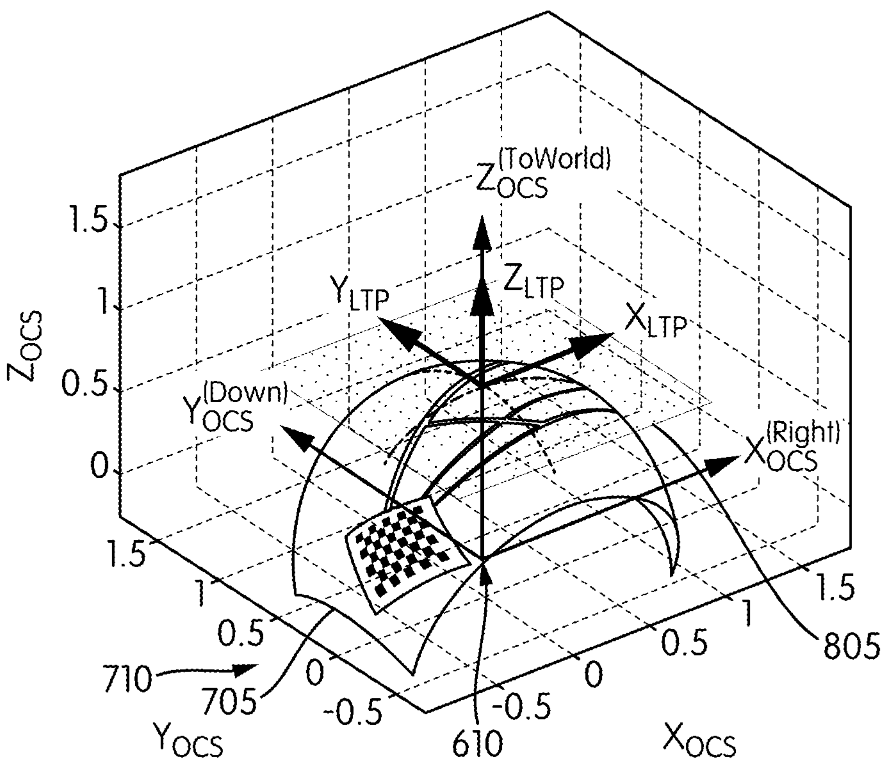
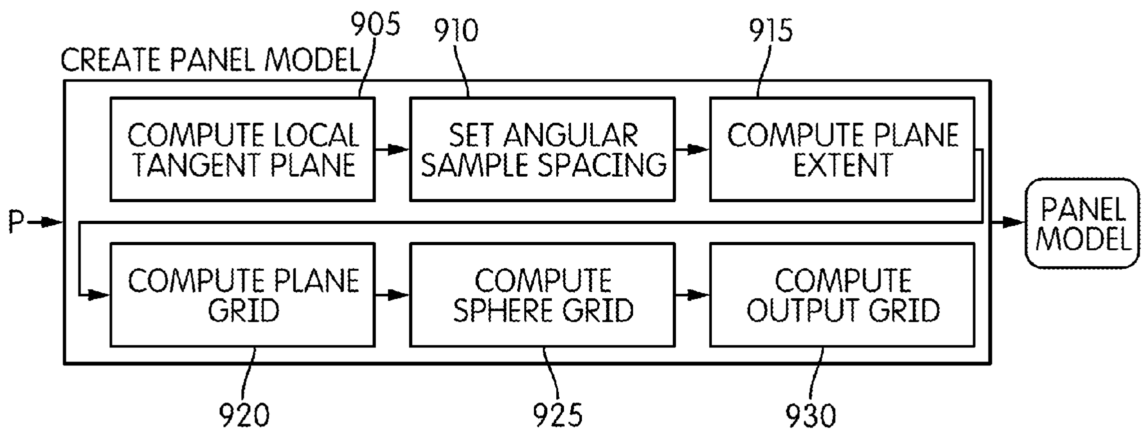

$Z_{OCS}^{(ToWorld)}$
1.5
1
0.5
0
Z_{OCS}
$Y_{OCS}^{(Down)}$
$X_{OCS}^{(Right)}$
1.5
1
0.5
0
-0.5
710
705
Y_{OCS}
610
-0.5
0
0.5
1
1.5
X_{OCS}

FIG. 7



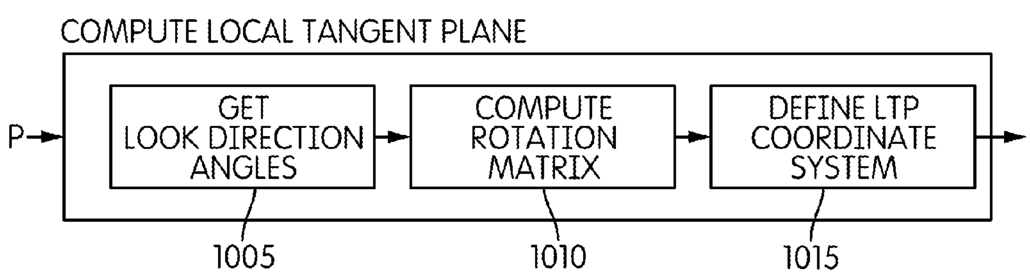
$Z_{OCS}^{(ToWorld)}$
Y_{LTP}
Z_{LTP}
X_{LTP}
$Y_{OCS}^{(Down)}$
$X_{OCS}^{(Right)}$
Z_{OCS}
Y_{OCS}
X_{OCS}
1.5
1
0.5
0
-0.5
710
705
610
805

FIG. 8



CREATE PANEL MODEL
905
910
915
COMPUTE LOCAL TANGENT PLANE
SET ANGULAR SAMPLE SPACING
COMPUTE PLANE EXTENT
P
PANEL MODEL
COMPUTE PLANE GRID
COMPUTE SPHERE GRID
COMPUTE OUTPUT GRID
920
925
930

FIG. 9



COMPUTE LOCAL TANGENT PLANE
P
GET LOOK DIRECTION ANGLES
COMPUTE ROTATION MATRIX
DEFINE LTP COORDINATE SYSTEM
1005
1010
1015

FIG. 10

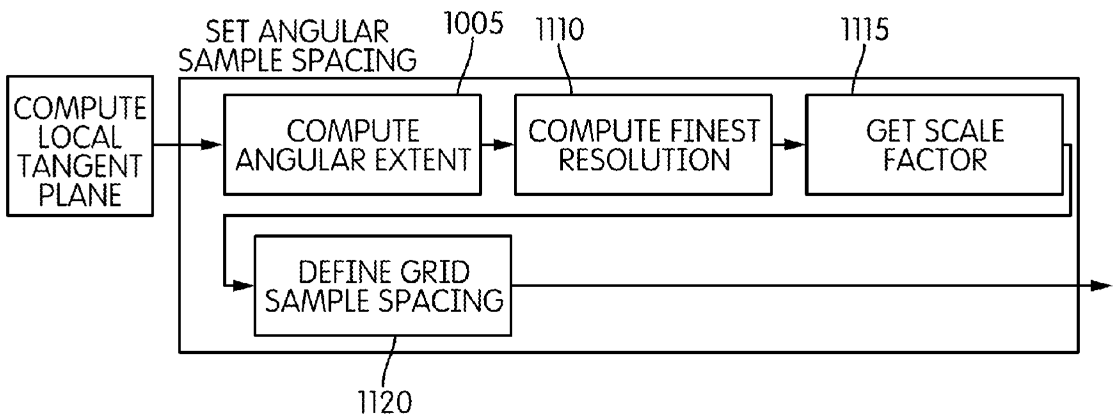

SET ANGULAR SAMPLE SPACING
1005
1110
1115
COMPUTE LOCAL TANGENT PLANE
COMPUTE ANGULAR EXTENT
COMPUTE FINEST RESOLUTION
GET SCALE FACTOR
DEFINE GRID SAMPLE SPACING
1120

FIG. 11

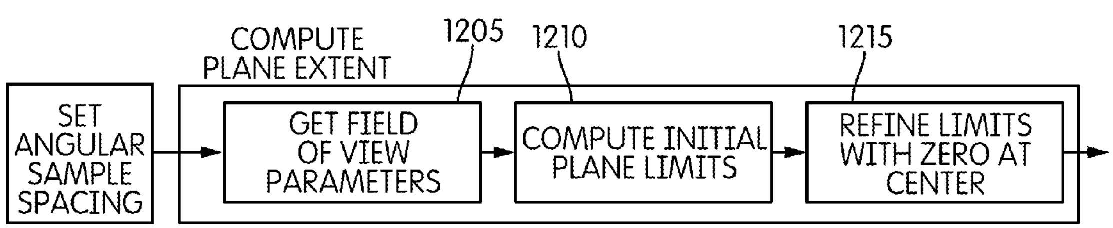

COMPUTE PLANE EXTENT
1205
1210
1215
SET ANGULAR SAMPLE SPACING
GET FIELD OF VIEW PARAMETERS
COMPUTE INITIAL PLANE LIMITS
REFINE LIMITS WITH ZERO AT CENTER

FIG. 12

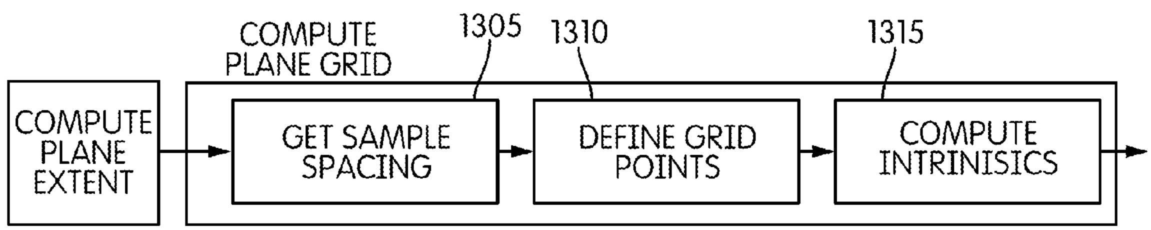

COMPUTE PLANE GRID
1305
1310
1315
COMPUTE PLANE EXTENT
GET SAMPLE SPACING
DEFINE GRID POINTS
COMPUTE INTRINISICS

FIG. 13

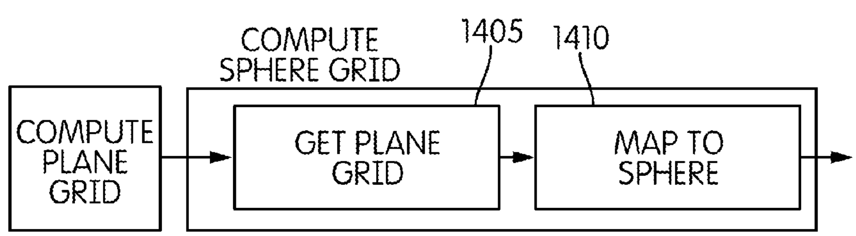
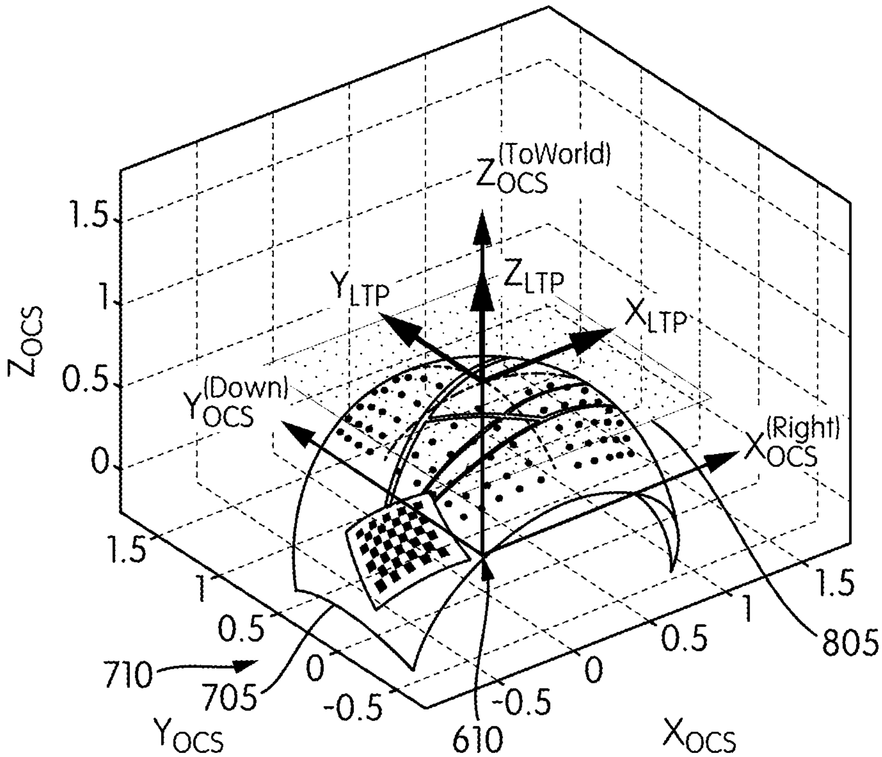
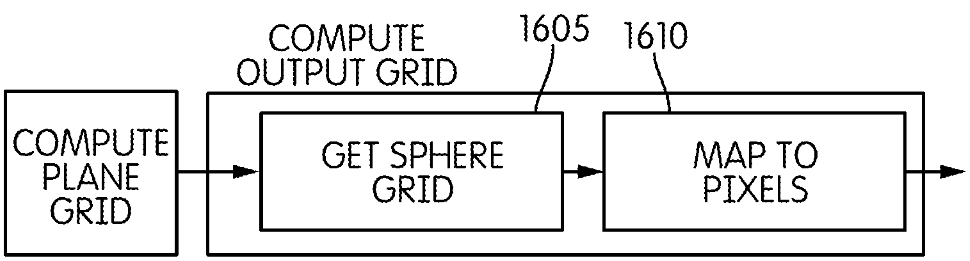

COMPUTE SPHERE GRID
1405
1410
COMPUTE PLANE GRID
GET PLANE GRID
MAP TO SPHERE

FIG. 14



$Z_{OCS}^{(ToWorld)}$
Z_{LTP}
Y_{LTP}
X_{LTP}
$Y_{OCS}^{(Down)}$
$X_{OCS}^{(Right)}$
Z_{OCS}
Y_{OCS}
X_{OCS}
1.5
1
0.5
0
-0.5
710
705
610
805

FIG. 15



COMPUTE PLANE GRID
COMPUTE OUTPUT GRID
1605
1610
GET SPHERE GRID
MAP TO PIXELS

FIG. 16

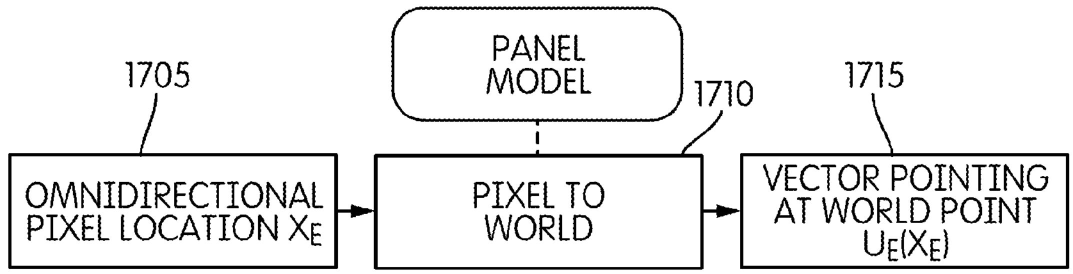


FIG. 17

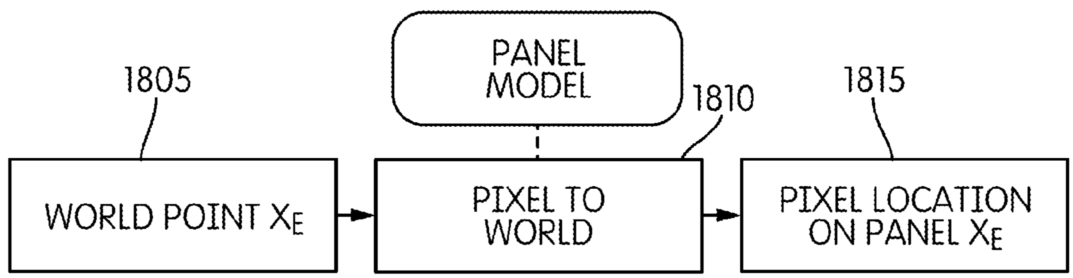


FIG. 18

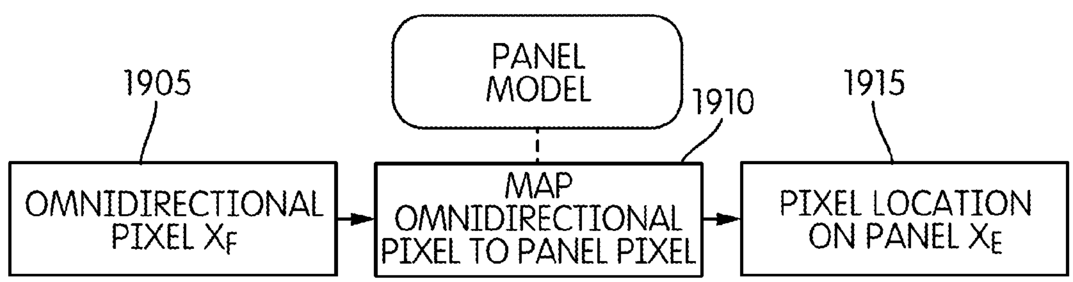


FIG. 19

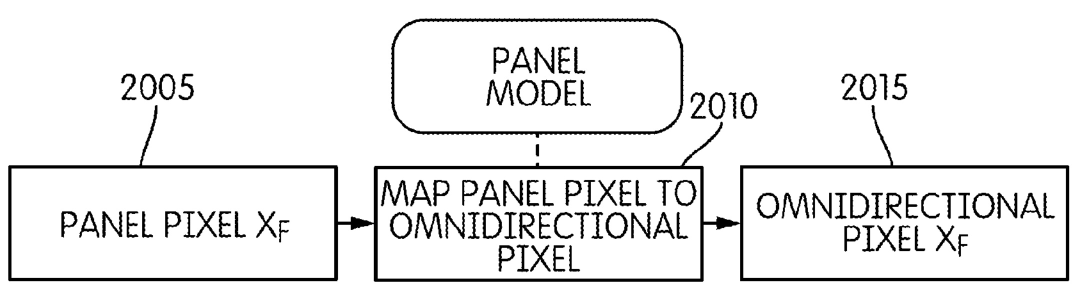


FIG. 20

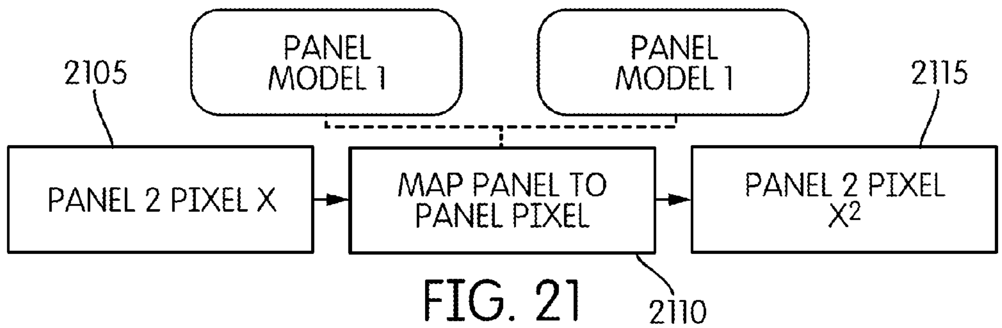


FIG. 21

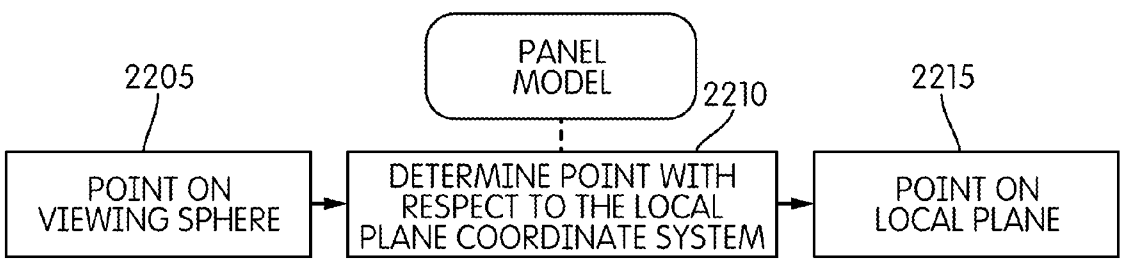


FIG. 22

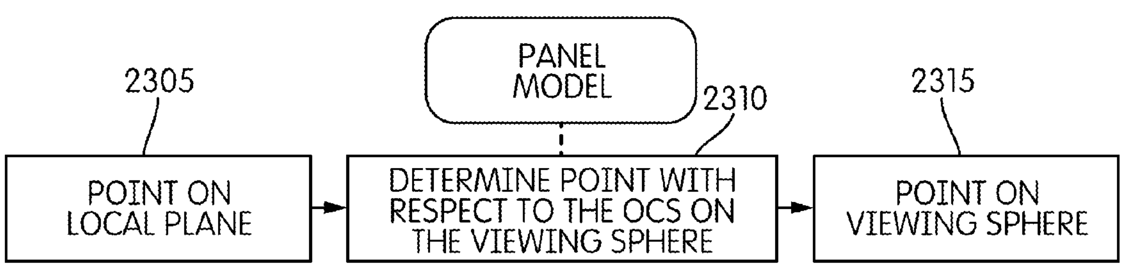


FIG. 23

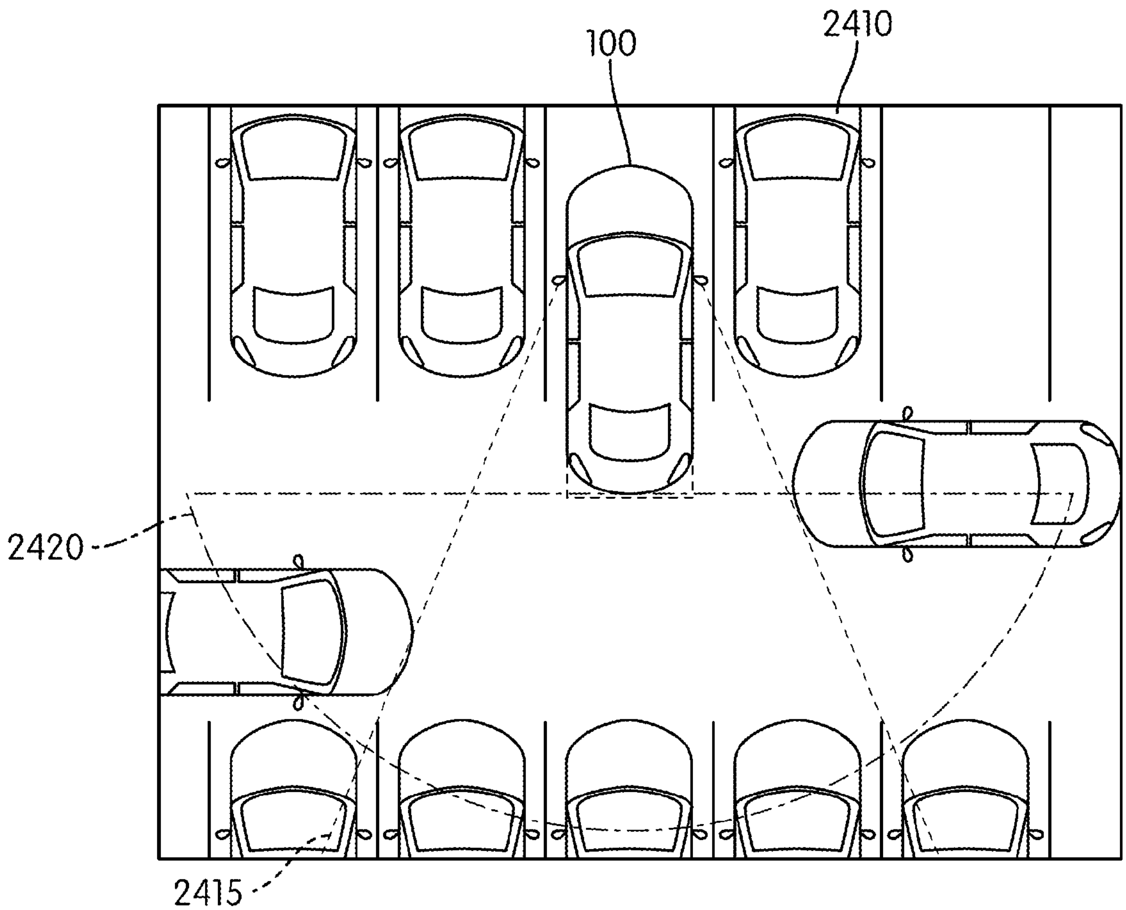


FIG. 24

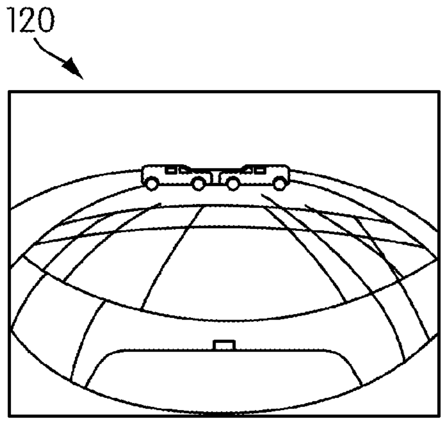


FIG. 25A

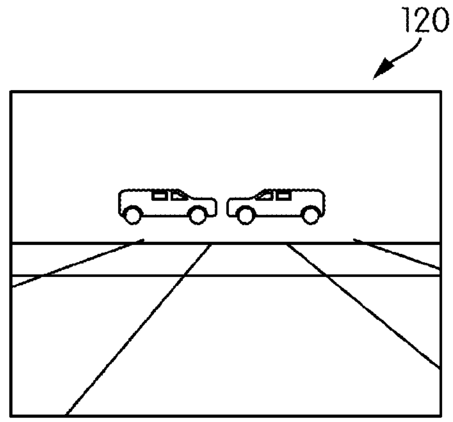


FIG. 25B

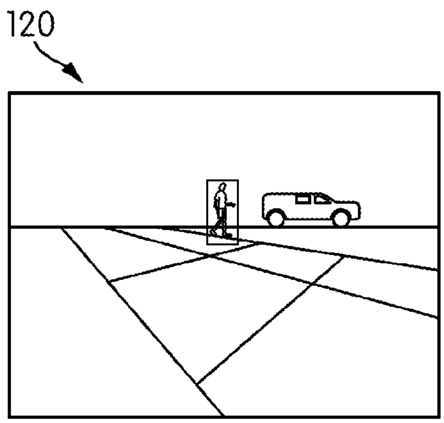


FIG. 25C

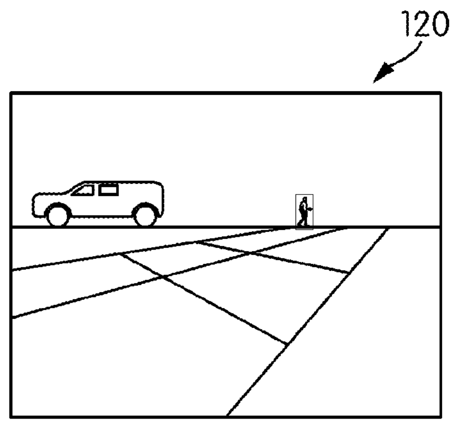


FIG. 25D

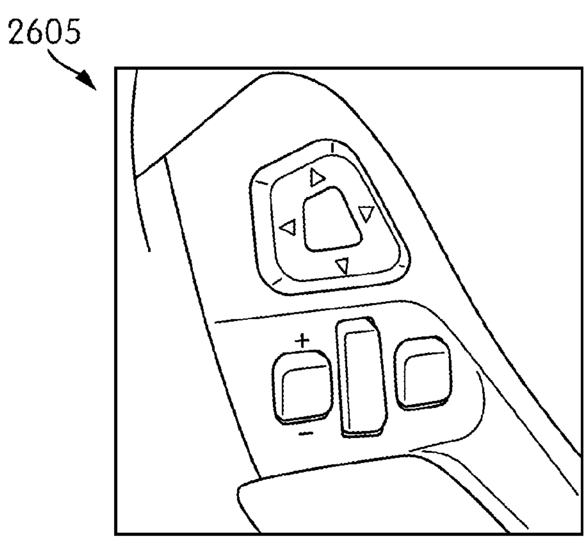


FIG. 26

REAL CROSS TRAFFIC—QUICK LOOKS

BACKGROUND

Embodiments of the invention relate to systems and methods of processing and displaying camera images. In particular, embodiments of the invention relate to converting an omnidirectional camera image to a rectilinear camera image.

SUMMARY

Vehicle imaging systems provide extended fields of view for a driver of a vehicle. A display screen located in the interior of the vehicle displays images from the vehicle's camera to the driver. For example, a rearview camera may be attached to a rear-portion of the vehicle. The rearview camera is configured to point rearward and downward such that objects directly behind the vehicle may be seen via the display. In this way, the driver can see objects behind the vehicle that are not directly visible due to blind spots in the driver's field of view.

One type of rear-view camera is an omnidirectional camera (e.g., a fish-eye lens camera). The omnidirectional camera captures an ultra-wide angle view. When mounted on the rear of a vehicle, some omnidirectional cameras can capture a field of view of 180 degrees behind the vehicle. The ultra-wide view allows the driver to detect vehicles approaching perpendicular to the driver's vehicle. This is particularly beneficial when a driver is backing the vehicle out of a parking space. In this scenario, adjacent, parked vehicles may obstruct the driver's field of view of cross-traffic. Using the rearview camera, the driver may exit the parking space with the aid of the display as the driver attempts to achieve natural visibility.

However, due to the lens of the omnidirectional camera, the image projected to the driver of the vehicle may be distorted. Due to this distortion, it is difficult for the driver to determine a distance between his vehicle and surrounding vehicles. In addition, a speed of surrounding vehicles is also hard to determine based on the omnidirectional image. Therefore, safety benefits are limited with displays that merely project the omnidirectional image to the driver.

Embodiments of the invention provide a system and method that transform regions of interest of the omnidirectional image into one or more rectilinear images. As part of the transformation, distortion that is present in the omnidirectional image is significantly reduced when displayed as the rectilinear image. Using the rectilinear image, the driver can judge the distance and speed of vehicles more accurately. In addition, the rectilinear image allows the driver to better assess the presence of other objects. For example, the driver can see and gauge the distance to pedestrians, poles, shopping carts, etc. through the rectilinear image.

Embodiments of the invention also provide a system and a method that transform between an omnidirectional image model and a rectilinear image model using a panel model defined by a parameter vector. The transformations include mapping between omnidirectional image pixels and rectilinear image pixels and world coordinates and image pixels. An electronic control unit computes the panel model and then performs various image processing functions using the panel model. These functions include providing the panel model to third-party software and hardware models that are configured to operate with rectilinear images. The panel presents a rectilinear image model by mathematically modeling a perspective view from an optical origin of the omnidirectional camera to a region of interest in the omnidirectional image.

In one embodiment, the invention provides a method of converting an omnidirectional image from an omnidirectional camera located on a vehicle to a rectilinear image by a control unit. The control unit accesses an omnidirectional camera model representative of an omnidirectional image on a unit sphere in an optical coordinate system. The omnidirectional camera model has a first plurality of pixels. The control unit receives a set of parameters defining a local plane tangent to the unit sphere. The local plane representative of a rectilinear camera model having a second plurality of pixels. The control unit determines a plane extent of the local plane based on the set of parameters with the plane extent defining a boundary of the local plane. Next, the control unit determines a relationship between the first plurality of pixels and the second plurality of pixels. The omnidirectional image from the omnidirectional camera is received, and the control unit generates a rectilinear image from the omnidirectional image based on the relationship between the first plurality of pixels and the second plurality of pixels.

Another embodiment of the invention provides a method of operating a vehicle imaging system. The method includes receiving, at an electronic control unit, an omnidirectional image from a vehicle-based omnidirectional camera. A first angular perspective vector is determined. A first rectilinear image orthogonal to the first angular perspective vector is then generated, and the first rectilinear image is displayed to a driver of the vehicle. The electronic control unit receives commands from a driver-operated control. The angular perspective vector is adjusted based on the commands. A second rectilinear image orthogonal to the adjusted angular perspective vector is generated, and the second rectilinear image is displayed to the driver.

In yet another embodiment, the invention provides a vehicle imaging system including an omnidirectional camera, a display, a driver-operated control, and an electronic control unit. The electronic control unit is configured to receive an omnidirectional image from the omnidirectional camera and determine a first angular perspective vector. The electronic control unit is further configured to generate a first rectilinear image orthogonal to the first angular perspective vector and send the first rectilinear image to the display. The electronic control unit is also configured to receive commands from the driver-operated control, adjust the angular perspective vector based on the commands, generate a second rectilinear image orthogonal to the adjusted angular perspective vector, and send the second rectilinear image to the display.

Other aspects of the invention will become apparent by consideration of the detailed description and accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is an illustration of a vehicle with a panel transform system.

FIG. **2** is a block diagram of an electronic control unit for the panel transform system of FIG. **1**.

FIG. **3** is a flowchart of a method of transforming an omnidirectional image to a rectilinear image using the panel transform system of FIG. **1**.

FIG. **4** is an omnidirectional image as inputted to an electronic control unit by an omnidirectional camera of FIG. **1** in the method of FIG. **3**.

FIG. **5** is a rectilinear image output by the method of FIG. **3**.

FIG. **6** is a 3D representation of an optical coordinate system in relation to the omnidirectional camera of the panel transform system of FIG. **1**.

FIG. **7** is a 3D representation of a viewing sphere displayed on the optical coordinate system of FIG. **6**.

FIG. **8** is a 3D representation of the viewing sphere of FIG. **7** and a local plane tangent to the viewing sphere.

FIG. **9** is a flowchart of a method of creating a panel model with the panel transform system of FIG. **1**.

FIG. **10** is a flowchart of a method of computing the local plane illustrated in FIG. **8**.

FIG. **11** is a flowchart of a method of setting an angular spacing for the method of FIG. **9**.

FIG. **12** is a flowchart of a method of computing a tangent plane extent for the method of FIG. **9**.

FIG. **13** is a flowchart of a method of computing a tangent plane grid for the method of FIG. **9**.

FIG. **14** is a flowchart of a method of computing a sphere grid for the method of FIG. **9**.

FIG. **15** is a 3D representation of a relationship of projected points between the viewing sphere and the local plane.

FIG. **16** is a flowchart of a method of computing an output grid for the method of FIG. **9**.

FIG. **17** is a flowchart of a method of converting an omnidirectional pixel location to a vector pointing to a world location using the panel model created from the method of FIG. **9**.

FIG. **18** is a flowchart of a method of converting a world location to a pixel location on the local plane using the panel model created from the method of FIG. **9**.

FIG. **19** is a flowchart of a method of converting a pixel location from an omnidirectional image to a pixel location on the local plane created from the method of FIG. **9**.

FIG. **20** is a flowchart of a method of converting a pixel location from the local plane to a pixel location on the omnidirectional image using the panel model created from the method of FIG. **9**.

FIG. **21** is a flowchart of a method of converting a pixel location from a first local plane to another pixel location from a second local plane using a first panel model and a second panel model.

FIG. **22** is a flowchart of a method of converting a point on the viewing sphere to a point on the local plane using the panel model created from the method of FIG. **9**.

FIG. **23** is a flowchart of a method of converting a point on the local plane to a point on the viewing sphere using the panel model created from the method of FIG. **9**.

FIG. **24** is an overhead view of a vehicle demonstrating the fields of view of the panel transform system of FIG. **1**.

FIG. **25**A is an omnidirectional image as inputted to an electronic control unit by an omnidirectional camera of FIG. **1**.

FIG. **25**B is a rectilinear image based on a transformation of the omnidirectional image of FIG. **25**A.

FIG. **25**C is a rectilinear image based on a transformation using a different perspective vector than illustrated in FIG. **25**B.

FIG. **25**D is a rectilinear image based on a transformation using yet another perspective vector than that illustrated in FIG. **25**B.

FIG. **26** is an example of driver-operated controls located on a steering wheel for adjusting the perspective vector of FIGS. **25**C-**25**D.

DETAILED DESCRIPTION

Before any embodiments of the invention are explained in detail, it is to be understood that the invention is not limited in its application to the details of construction and the arrangement of components set forth in the following description or illustrated in the following drawings. The invention is capable of other embodiments and of being practiced or of being carried out in various ways.

It should be noted that a plurality of hardware and software based devices, as well as a plurality of different structural components may be used to implement the invention. In addition, it should be understood that embodiments of the invention may include hardware, software, and electronic components or modules that, for purposes of discussion, may be illustrated and described as if the majority of the components were implemented solely in hardware. However, one of ordinary skill in the art, and based on a reading of this detailed description, would recognize that, in at least one embodiment, the electronic based aspects of the invention may be implemented in software (e.g., stored on non-transitory computer-readable medium) executable by one or more processors. As such, it should be noted that a plurality of hardware and software based devices, as well as a plurality of different structural components may be utilized to implement the invention. For example, "control units" and "controllers" described in the specification can include one or more processors, one or more memory modules including non-transitory computer-readable medium, one or more input/output interfaces, and various connections (e.g., a system bus) connecting the components.

The use of imaging systems is becoming more prolific in modern vehicles. Increasingly, modern vehicles include one or more omnidirectional cameras (e.g., fish-eye lens camera) on the vehicle's exterior to provide wide-angle views around the vehicle. An omnidirectional camera provides a greater field of view than a traditional rectilinear camera. However, the omnidirectional camera captures an image that appears distorted compared to an image captured by a rectilinear camera due to nonlinearities in the image. For example, parallel lines, such as lane markings on a road, appear curved in the image produced by the omnidirectional camera. Often, these camera images are displayed to a driver of the vehicle to increase the driver's awareness of the surroundings. However, when an omnidirectional image is displayed to the driver, the driver may have difficulty gauging distances and speeds of surrounding vehicles based solely on the omnidirectional image.

Some of the systems or methods described herein provide a panel transform that converts an omnidirectional image captured from an omnidirectional camera to a rectilinear image for display to the driver. The rectilinear image contains corrections of the distortion from the omnidirectional image. The corrected image aids the driver in properly gauging distance and speeds of other vehicles. This is particularly useful when the driver is backing out of a parking space. In this situation, the driver's vision may be obscured by vehicles parked adjacent to his vehicle. A vehicle equipped with a rearview, omnidirectional camera may allow the driver to view vehicles obscured by the adjacent vehicles, for example, vehicles approaching perpendicular to the vehicle. So that the driver can properly ascertain the approaching vehicles distance and speed, the omnidirectional image is transformed to a rectilinear image prior to display to the driver.

The panel transform first establishes a region of interest in the omnidirectional image. Once the region of interest is defined, the panel transform converts a portion of the omnidirectional image into the rectilinear image with the methods presented herein. The transformation of the portion of the image is enabled by first mapping a relationship between the region of interest in the omnidirectional image and a perspective view of that region of interest. The mapping provides the panel transform with an ability to perform an array of functions relating to the omnidirectional image.

FIG. **1** illustrates a vehicle **100** equipped with an embodiment of the panel transform. The vehicle **100** includes an omnidirectional camera **105**, an electronic control unit (ECU **110**), a vehicle communication bus **115** (e.g., a CAN bus), a display **120**, and an input interface **125**. Some embodiments also include a steering wheel **130** and a steering angle sensor **135** configured to provide an input signal to the ECU **110**. The camera **105** is communicatively coupled to the ECU **110**, whereby the ECU **110** accesses a plurality of images captured with the camera **105**. The plurality of images may be a continuous video stream or a sequence of still images. The ECU **110** processes the plurality of images from the camera **105** and sends processed images to the display **120** for viewing by the driver of the vehicle. The communication bus **115** communicatively couples the ECU **110** with the display **120** along with other vehicle systems. The communication bus **115** thus enables communication between the ECU **110**, the display **120**, the input interface **125**, and other vehicle systems. In some embodiments, the display **120** and the input interface **125** are combined into a single unit. For example, the input interface **125** can receive commands from the driver via a touchscreen on the display **120**.

FIG. **2** is a block diagram of the ECU **110** of the panel transform. The ECU **110**, among other things, is configured to transform portions of the omnidirectional images into rectilinear images. The ECU **110** includes a plurality of electrical and electronic components that provide power, operation control, and protection to the components and modules within the ECU **110** and/or the camera **105**. For example, the ECU **110** includes, among other things, a controller **205** (such as a programmable electronic microprocessor, microcontroller, or similar device), a power supply module **210**, and an input/output module **215**. The controller **205** includes, among other things, a processing unit **220** and a memory **225**. The processing unit **220** is communicatively coupled to the memory **225** and executes instructions which are capable of being stored on the memory **225**. The controller **205** is configured to retrieve from memory **225** and execute, among other things, instructions related to the control processes and method described herein. In other embodiments, the ECU **110** includes additional, fewer, or different components.

In the embodiment of FIG. **2**, the input/output module **215** receives the omnidirectional images from the camera **105** and transmits the omnidirectional images to the controller **205** for image processing. The controller **205** then processes and transforms the images based on internal protocols and external commands. The ECU **110** transmits transformed images to the display **120** either via the communication bus **115** or another communications link between the ECU **110** and the display **120**. In addition, the input/output module **215** receives commands from the input interface **125** identifying a region of interest of the omnidirectional image. The region of interest of the omnidirectional image represents a portion of the omnidirectional image that is determined, by the ECU **110** and/or the driver, to be particularly relevant to the driver at that point in time.

The input interface **125** includes driver controls **240** that enable the driver to manually select the region of interest of the omnidirectional image. The driver controls **240** may include, for example, buttons, dials, or joysticks. Often, the driver controls **240** are positioned in a convenient position for the driver, for example, on the steering wheel **130**, on a center console, or on a dashboard. In particular, media keys for audio controls located on the steering wheel **130** may be configured to allow the driver to manually select the region of interest. In such embodiments, the controls perform dual-purpose functions, which each function being selected in various modes. For example, in a first mode, the media keys operate the audio controls, and in a second mode, the media keys input a signal defining the region of interest to the ECU **110**. In such an example, the first mode may be default mode, and the second mode may be activated by a manual switch or by automatic activation upon a triggering event, such as putting the vehicle in a reverse gear.

In some embodiments, the input interface **125** does not include driver controls **240**. Rather, the ECU **110** receives data from automated vehicle systems. The automated vehicle systems may automatically define the region of interest of the omnidirectional image. For example, a steering angle sensor **135** may input steering angle data to the ECU **110**. Using the steering angle data, the ECU **110** is able to predict a direction of travel of the vehicle and to select the region of interest based on the predicted direction of travel. In other embodiments, both driver controls **240** and automated vehicle systems are used to define the region of interest. These systems may be used in cooperation or with assigned priorities. For example, when the vehicle is in reverse gear, the ECU **110** may determine the region of interest based on the steering angle data. Then, when activated, the driver controls **240** may override the region of interest determined based on the steering angle data. In such an embodiment with cooperative control, the driver controls **240** and the steering angle data may both assist in determining the region of interest. The cooperative control may have the steering angle sensor **135** and the driver controls **240** assigned different weights depending on predetermined priorities.

The input interface **125** may be linked through a communication module on the communication bus **115**. In some embodiments, the input interface **125** communicates by means of a protocol such as J1939 or CAN bus for communicating with the input/output module **215**. In other embodiments, the input interface **125** communicates with the input/output module **215** under other suitable protocols depending on the needs of the specific application. In some embodiments, the input interface **125** inputs information from various automotive controls and sensors.

FIG. **3** illustrates a method of transforming a portion of the omnidirectional image captured by the camera **105** into a rectilinear image. In a first step, the ECU **110** loads the omnidirectional image from the camera **105** and loads a panel model (described below) (step **305**). In a second step, the ECU **110** maps a portion of the omnidirectional image to the rectilinear image based on the panel model (step **310**). In other words, the ECU **110** runs a warp routine to warp each pixel location of the portion of the omnidirectional image to a corresponding pixel location of the rectilinear image based on the panel model. In the process, the ECU **110** copies information from each pixel of the portion of the omnidirectional image to the corresponding rectilinear pixel. In a third step, a panel image (i.e., the rectilinear image) is generated and outputted (step **315**). The output may then be sent to the display **120**. It should be noted that this method of FIG. **3** may be repeated for additional panel models. Each panel model may describe a different portion of the omnidirectional image. When the ECU **110** outputs multiple rectilinear images based on multiple panel models, the display **120** may display multiple rectilinear images in various configurations.

FIG. **4** illustrates an omnidirectional camera image before the transformation described in FIG. **3**. As previously discussed, the omnidirectional image contains nonlinearities in the image. For example, a checkerboard **405** illustrates a how an omnidirectional image displays parallel lines. As illustrated, a top **410** and a left-side **415** of the checkerboard **405** are bowed outward. Conversely, a bottom **420**, and a right-side **425** are bowed inward. In contrast, the omnidirectional image is illustrated after the transformation in FIG. **5**. As the transformed image illustrates, a checkerboard **505** illustrates correction of the nonlinearities of the checkerboard **405**. A top **510**, a left-side **515**, a bottom **520**, and a right-side **525** of the checkerboard **505** approximate straight edges as captured by a rectilinear camera. An area **530** is a region of the image that is out of a field of view of the camera **105**.

In other embodiments, the ECU **110** performs various transformations based on information from the omnidirectional image to enable different functions both within the ECU **110** and by other vehicle systems and controllers external to the imaging system. A reference frame is illustrated in FIG. **6**. The reference frame includes an optical coordinate system (OCS) with coordinate [0,0,0] positioned at an optical origin **610**. The optical origin **610** represents a center point where the camera **105** detects light from its surroundings (e.g., a pinhole camera). As illustrated, a Z-axis extends straight out along a center of a line of sight of the camera **105**. A Y-axis extends downward and perpendicular to the center line of sight. An X-axis extends to the right side and perpendicular to the camera **105**. This system of coordinates allows analysis of real-world positions by the ECU **110**.

Prior to operation, a calibration procedure is performed to align the OCS with the optics of the camera **105**. The calibration procedure uses a predefined pattern captured by the omnidirectional image. For example, calibration may use the checkerboard **405** to align the OCS with the omnidirectional image. During calibration, world locations represented by the checkerboard **405** and defined with respect to the OCS are mapped to pixel locations. Pixel locations are also mapped to vectors that point towards the corresponding world point (e.g., a position on the checkerboard **405**).

FIG. **7** illustrates an omnidirectional image **705** displayed as a viewing sphere **710** overlaid on the OCS. In other words, the viewing sphere **710** represents the omnidirectional image **705** as received by the camera **105** within the OCS. The viewing sphere **710** may be an area defined by a set of vectors from the optical origin **610** with a magnitude of 1 unit (i.e., a unit sphere). The viewing sphere **710** provides a visual representation of the omnidirectional image **705**. A plurality of pixels that form the omnidirectional image **705** are positioned within the area defined by the viewing sphere **710**. It should be noted that while the viewing sphere **710** is theoretically contiguous, a maximum resolution of the omnidirectional image **705** depends on a quantity of the plurality of pixels. The quantity of pixels depending on the type of camera **105**. In one embodiment, the ECU **110** stores the omnidirectional image **705** in memory **225** in a table of values based on a pixel location on the viewing sphere **710**. The pixel location may be described in reference to the optical origin **610** (e.g., as a vector) or as a coordinate point on the viewing sphere **710**.

A local plane **805** tangent to the viewing sphere **710** is illustrated in FIG. **8**. The local plane **805** is defined by a set of parameters loaded into the ECU **110**. In one embodiment, the set of parameters includes values that describe a direction and orientation of the local plane **805**, a vertical field of view, a horizontal field of view, and a scale factor. In such an embodiment, the direction and orientation of the local plane **805** may be defined by a yaw, pitch, and roll angle from the optical origin **610** or from angles from the optical coordinate axes. In this way, the direction of the local plane **805** is given by a parameter vector that points toward the center of the local plane **805**. The vertical and horizontal fields of view may each be defined by an angle with the parameter vector intersecting the angle. The ECU **110** may store the set of parameters in the memory **225** in the form of a vector:

$$P=[P_{\psi_Y} P_{\psi_P} P_{\psi_R} P_{\theta_V} P_{\theta_H} P_{\Delta}]^T \quad (1)$$

where $\{P_{\psi_Y}, P_{\psi_P}, P_{\psi_R}\}$ represent yaw, pitch, and roll respectively, $\{P_{\theta_V}, P_{\theta_H}\}$ represent the vertical and horizontal field of view (e.g. $P_{\theta_V}=P_{\theta_H}=100°$), and P_{Δ} is a scale factor that controls the resolution. In other words, $\{P_{\psi_Y}, P_{\psi_P}, P_{\psi_R}\}$ define the panel direction and orientation.

Once the set of parameters are defined by values, the local plane **805** may be transformed into a panel model. The panel model specifies an area of interest tangent to the viewing sphere **710** in reference to the OCS, and thereby also specifies an area of interest on the viewing sphere **710**. The panel model may be defined by an intrinsic matrix of the form:

$$K = \begin{bmatrix} \alpha_x & 0 & x_0 \\ 0 & \alpha_y & y_0 \\ 0 & 0 & 1 \end{bmatrix} \quad (2)$$

where α_x and α_y represent scaling parameters, and $[x_0\ y_0]^T$ is the point where the parameter vector intersects the local plane **805**. The panel model represents a virtual perspective camera pointed in the direction of the parameter vector with the parameter vector originating at the optical origin **610**. The panel model may include all of the information given by the set of parameters including direction, field of view, and resolution.

FIG. **9** illustrates a method of determining the panel model based on the set of parameters. The ECU **110** computes the local plane **805** to the viewing sphere **710** based on the set of parameters (step **905**). The ECU sets angular sample spacing of the local plane **805** (step **910**). The ECU **110** calculates a plane extent of the local plane **805** (step **915**). The ECU **110** determines a local plane grid (step **920**). The ECU **110** determines a sphere grid based on the local plane grid (step **925**). The ECU determines an output grid (step **930**). The ECU determines the panel model based on the output grid (step **935**).

FIGS. **10-15** illustrate particular steps of the method illustrated in FIG. **9**. In reference to step **905**, FIG. **10** illustrates a method of computing the local plane **805**. As described previously, the local plane **805** lies on top of the viewing sphere **710**. The local plane **805** is determined by angular coordinates $[P_{\psi_Y}\ P_{\psi_P}\ P_{\psi_R}]^T$. The angular coordinates are specified by the user-defined parameters as discussed above. To compute the local plane **805**, the ECU **110** determines the direction specified by the set of parameters (step **1005**). The ECU **110** computes a rotation matrix (step **1010**). Lastly, the ECU **110** defines a local plane coordinate system with an origin at the contact point between the parameter vector and the viewing sphere **710** (step **1015**). In one embodiment, an initial basis {X, Y, Z} is determined as follows:

$$X'=[1\ 0\ 0]^T$$

$$Y'=[0\ 1\ 0]^T$$

$$Z'=X'\times Y' \tag{3}$$

Using these values, the yaw angle is applied from the parameters as follows:

$$X''=R_y(P_{\psi Y})X' \tag{4}$$
$$Y''=R_y(P_{\psi Y})Y'$$
$$Z''=R_y(P_{\psi Y})Z'$$

where

$$R_y(\theta)\triangleq\begin{bmatrix}\cos\theta & 0 & \sin\theta\\ 0 & 1 & 0\\ -\sin\theta & 0 & \cos\theta\end{bmatrix} \tag{5}$$

The pitch angle is also applied from the parameters as follows:

$$X'''=R_y(P_{\psi P})X'' \tag{6}$$
$$Y'''=R_y(P_{\psi P})Y''$$
$$Z'''=R_y(P_{\psi P})Z''$$

where

$$R_x(\theta)\triangleq\begin{bmatrix}1 & 0 & 0\\ 0 & \cos\theta & -\sin\theta\\ 0 & \sin\theta & \cos\theta\end{bmatrix} \tag{7}$$

Similarly, the roll angle is applied from the parameters as follows:

$$X_{LTP}=R_z(P_{\psi R})X''' \tag{8}$$
$$Y_{LTP}=R_z(P_{\psi R})Y'''$$
$$Z_{LTP}=R_z(P_{\psi R})Z'''$$

where

$$R_z(\theta)\triangleq\begin{bmatrix}\cos\theta & -\sin\theta & 0\\ \sin\theta & \cos\theta & 0\\ 0 & 0 & 1\end{bmatrix} \tag{9}$$

It should be noted that the steps above apply rotation matrixes in an arbitrary order. The steps may be performed in alternative orders. After applying the rotation matrixes, the ECU **110** determines the local plane **805** $\{X_{LTP}, Y_{LTP}, Z_{LTP}\}$ based on the following:

$$[X_{LTP}Y_{LTP}Z_{LTP}]=R_z(R_{\psi R})R_x(P_{\psi P})R_y(P_{\psi Y}) \tag{10}$$

In a general sense, rotation matrices belong to the orthogonal group O(n), and therefore, the expression may be simplified as:

$$[X_{LTP}Y_{LTP}Z_{LTP}]=\tilde{R} \tag{11}$$

where $\tilde{R}\epsilon O(3)$ represents an arbitrary rotation matrix such that $\tilde{R}^T\tilde{R}=I$. The local plane coordinate system is then encoded by the ECU **110** in the following matrix:

$$M_{LTP}=\begin{bmatrix}[X_{LTP}Y_{LTP}Z_{LTP}] & Z_{LTP}\\ 0^T & 1\end{bmatrix}=\begin{bmatrix}\tilde{R} & \tilde{R}[0\ 0\ 1]^T\\ 0^T & 1\end{bmatrix} \tag{12}$$

where M_{LTP} is a function called by the ECU **110** to transform a homogenous point or vector described by the local plane coordinate system to a homogenous point or vector described by the OCS.

After computing the local plane **805**, the ECU **110** sets constant angular sample spacing using the steps illustrated in FIG. **11**. The ECU **110** computes the angular extent (step **1105**). The ECU **110** computes finest resolution (step **1110**). Then, the ECU **110** reads the scale factor from the parameters (step **1115**). Lastly, the ECU **110** defines grid sample spacing (step **1115**). One embodiment for determining the constant angular sample spacing using steps **1105** through **1115** is illustrated in the steps that follow. Let h and w represent the height and width of the omnidirectional image **705**. Then c and r are defined as follows:

$$c=linspace\left(0,\frac{w}{2}\right) \tag{13}$$

$$r=linspace\left(0,\frac{h}{2}\right) \tag{14}$$

The angular extent is computed as follows:

$$\theta_x=a\tan 2(c,-F(c)) \tag{15}$$

$$\theta_y=a\tan 2(r,-F(r)) \tag{16}$$

where F represents a forward projection function computed during the calibration procedure. The sample spacing is not uniform; however, using a simplification that it is, the sample spacing would be calculated as follows:

$$\mu_x=\frac{\max(\theta_x)}{w/2} \tag{17}$$

$$\mu_y=\frac{\max(\theta_y)}{h/2} \tag{18}$$

The finest resolution is determined.

$$\mu_\theta=\min(\mu_x,\mu_y) \tag{19}$$

where μ_θ represents an ideal angular gridded support for the omnidirectional image **705**. Next, the sample spacing on the local tangent plane is determined as follows:

$$\Delta=P_\Delta\tan\left(\frac{\mu_\theta}{2}\right) \tag{20}$$

where $P_\Delta>1$ stretches the sample spacing, and $P_\Delta<1$ compresses the sample spacing. As the sample spacing is stretched, the resolution of the image decreases, and conversely, as the sample spacing is compressed, the resolution increases.

The next step in determining the panel model is to compute a plane extent. The method of computing a plane extent is illustrated in FIG. **12**. The ECU **110** loads the vertical and horizontal angles describing a field of view from the optical origin **610** based on the set of parameters (step **1205**). The ECU **110** computes initial plane limits that define a boundary of the local plane **805** (step **1210**). Lastly, the ECU **110** refines the initial plane limits by positioning zero at the center (step **1215**). One embodiment of the method **1200** uses the following steps and equations. First, determine the extent of the local plane **805** with respect to the field of view parameters $[P_{\theta_V}, P_{\theta_H}]^T$. In other words, a complete perimeter of the local plane **805** is defined with limits that extend to the field of view defined by the vertical and horizontal angles. In one embodiment, the limits of the plane are determined by the following steps and equations.

$$x'_{lim} = [-1\ \ 1]\tan^{-1}\frac{P_{\psi_{LR}}}{2} \quad (21)$$

$$y'_{lim} = [-1\ \ 1]\tan^{-1}\frac{P_{\psi_{UD}}}{2} \quad (22)$$

The limits of the plane are modified to explicitly contain zero (see section below) using the equations presented as follows.

$$x''_{lim} = \text{round}\left(\frac{x'_{lim}}{\Delta}\right) \quad (23)$$

$$y''_{lim} = \text{round}\left(\frac{y'_{lim}}{\Delta}\right) \quad (24)$$

which yields

$$x_{lim} = x''_{lim}\Delta \quad (25)$$

$$y_{lim} = y''_{lim}\Delta \quad (26)$$

In other words, the plane extent (i.e., the total area spanned by the local plane **805**) is given by

$$A_{LTP} = \|x_{lim}\|\|y_{lim}\| \quad (27)$$

The next step in determining the panel model is to compute the plane grid. The method of computing the plane grid is illustrated in FIG. **13**. The ECU **110** loads the constant angular sample spacing from memory **225** (step **1305**). The ECU **110** defines grid points (step **1310**). Lastly, the ECU **110** computes intrinsic parameters of the camera **105** (step **1315**). An embodiment of the method uses the following steps and equations. The ECU **110** calculates a set of grid points on the local plane **805**. Each grid point corresponds to a world point of interest and has a corresponding pixel mapped to it. The ECU **110** determines an intrinsic matrix K. The ECU **110** computes the local plane grid by first determining the following vectors:

$$x_{LTP} = x_{lim}[1]:\Delta:x_{lim}[2] \quad (28)$$

$$y_{LTP} = y_{lim}[1]:\Delta:y_{lim}[2] \quad (29)$$

A local plane plaid grid is given by:

$$\{x_{LTP}, y_{LTP}\} = \text{meshgrid}(x_{LTP}, y_{LTP}) \quad (30)$$

where meshgrid is a standard MATLAB function, and x_{LTP} and y_{LTP} are matrices that store the grid points in the so-called plaid format. The grid is transformed to OCS using the following calculation:

$$\begin{bmatrix} x_{OCS}(:)^T \\ y_{OCS}(:)^T \\ z_{OCS}(:)^T \\ 1^T \end{bmatrix} = M_{LTP}\begin{bmatrix} x_{LTP}(:)^T \\ y_{LTP}(:)^T \\ 0^T \\ 1^T \end{bmatrix} \quad (31)$$

The internal camera parameters are given by the equation:

$$k_x = k_y = \frac{1}{\Delta} \quad (32)$$

Since the viewing sphere **710** is defined as a unit sphere, the focal length is normalized to unity (i.e., f=1). The ECU **110** sets pixel scale parameters using the following equations:

$$\alpha_x = fk_x \quad (33)$$

$$\alpha_y = fk_y \quad (34)$$

The intrinsic matrix is expressed in the following form:

$$K = \begin{bmatrix} \alpha_x & 0 & x_0 \\ 0 & \alpha_y & y_0 \\ 0 & 0 & 1 \end{bmatrix} \quad (35)$$

The next step in determining the panel model is computing the sphere grid. FIG. **14** illustrates a method to compute the sphere grid. In a first step, the ECU **110** loads the plane grid (step **1405**). In a second step, the ECU **110** maps the local plane grid to the viewing sphere **710** (step **1410**). An embodiment of the method **1400** uses the following steps and equations. The spherical grid is computed by projecting the local plane grid $\{x_{OCS}, y_{OCS}, z_{OCS}\}$ to the viewing sphere **710** $\{x_{sph}, y_{sph}, z_{sph}\}$ and defining the local plane grid with respect to the OCS. As an example, FIG. **15** illustrates the projected points $\{x_{sph}, y_{sph}, z_{sph}\}$ on the viewing sphere **710**. The spherical grid $\{x_{sph}, y_{sph}, z_{sph}\}$ is computed by normalizing each grid sample (i,j) of the local plane grid $\{x_{OCS}, y_{OCS}, z_{OCS}\}$ with the following equation:

$$\begin{bmatrix} x_{sph}[i,j] \\ y_{sph}[i,j] \\ z_{sph}[i,j] \end{bmatrix} = \frac{[x_{OCS}[i,j]\,y_{OCS}[i,j]\,z_{OCS}[i,j]]^T}{\|[x_{OCS}[i,j]\,y_{OCS}[i,j]\,z_{OCS}[i,j]]^T\|} \quad (36)$$

In other words, a point on the plane $p_{plane}[i,j]=[x_{OCS}[i,j]\ y_{OCS}[i,j]\ z_{OCS}[i,j]]^T$ will have an L2 norm of $\mu p_{plane}[i,j]\|\geq 1$ and by normalizing, such that $\|p_{plane}[i,j]\|=1\ \forall i,j$ all points are projected to the viewing sphere **710**.

In a last step for determining the panel model, the ECU **110** computes the output grid as illustrated in FIG. **16**. In a first step, the ECU **110** loads the sphere grid (step **1605**). In a second step, the ECU **110** maps the sphere grid to pixels on the viewing sphere **710** (step **1610**). Mapping the sphere grid to pixels may include a process of interpolation using look-up tables. The ECU **110** then computes the panel model. The panel model represents a virtual camera perspective model. In other words, the panel model is a mathematical model of a viewing plane captured from the origin of the omnidirectional camera.

It should be noted that the ECU **110** may compute multiple panel models in parallel based on multiple sets of parameters. When multiple panel models are determined, the ECU **110** calculates each panel model separately based on each set of parameters. Each set of parameters may be determined independently based on various automatic or manual inputs. Some of the panel models may be held constant (at a set parameter vector) while others are repositioned and recalculated based on moving parameter vectors. The ECU **110** may output parallel rectilinear images based on the multiple panel models to the display **120** to display multiple different rectilinear images simultaneously. Alternatively, the ECU **110** may output multiple panel models for various functions relating to image processing.

The panel model allows the ECU **110** to perform various functions involving the omnidirectional image **705**. For example, FIG. **17** illustrates a method **1700** of converting a panel pixel location x_E to a vector pointing to a position in the world. The function back-transforms a pixel on the local panel **805** to a vector defined with respect to the OCS that points to a world point $U_E(X_E)$. In other words, if X represents a world location defined with respect to the OCS, and x represents the pixel that corresponds to this location, then this function forms

$$u_E(x) = \frac{X}{\|X\|},$$

a vector pointing toward the world point. In a first step, the ECU **110** loads the omnidirectional pixel location from memory **225** (step **1705**). In a second step, the ECU **110** calculates the vector pointing to a world location based on the panel model (step **1710**). Third, the ECU **110** outputs the vector (step **1715**). In one embodiment, the ECU **110** calculates the vector based on the following set of steps and equations. Given a panel pixel x_E, transform it to homogenous form

$$x = \begin{bmatrix} x_E \\ 1 \end{bmatrix}.$$

Back project this pixel to form a ray. A point on this ray is given by the expression:

$$p=P^{\dagger}x \tag{37}$$

where $P^{\dagger}$ represents the pseudo-inverse of P=[K 0]. The homogenous world point p is transformed to Euclidian form, and denoted as p_E. Since a world location could be located at any point along the ray, normalize with the following convention:

$$v_E = \frac{p_E}{\|p_E\|} \tag{38}$$

To determine if the vector points towards the world point or away from the world point, perform a dot product of the world Z basis. If the result is positive, the ray points toward the world point. Conversely, if the result is negative, the ray points away from the world point. This result can be determined by the following expression:

$$s=\text{sign}([0\ 0\ 1]v_E) \tag{39}$$

A corrected vector is given by given by sv_e expressed with respect to the local plane coordinate system. The vector may be expressed with respect to the OCS by using the following relationship:

$$u_E=sR_{LTP}^{OCS}v_E \tag{40}$$

where $R_{LTP}^{OCS}=\tilde{R}$ from the expression defined above for M_{LTP}.

In an example, which is illustrated in FIG. **18**, the ECU **110** determines a pixel location on a panel from a world location defined with respect to the OCS based on the panel model. The panel refers to a plane aligned with the local plane **805** defined in terms of pixels, while the local plane **805** is defined in terms of distance (e.g. meters). In a first step, the ECU **110** loads a world point X_E (step **1805**). In a second step, the ECU **110** determines a pixel location on the panel based on the panel model (step **1810**). In a third step, the ECU **110** outputs the pixel location (step **1815**). The determination of the pixel location may be performed based on the following steps and equations. Rotate the world point X_E into the local plane coordinate system:

$$X'_E=R_{OCS}^{LTP}X_E \tag{41}$$

where $R_{OCS}^{LTP}=(R_{LTP}^{OCS})^T$. Transform to homogenous form

$$X = \begin{bmatrix} X'_E \\ 1 \end{bmatrix}$$

and map it to the pixel location with the following expression:

$$x=[K0]X \tag{42}$$

The homogenous pixel x is then transformed to Euclidian form x_E.

In yet another example, the ECU **110** determines a pixel location on the panel from a pixel location on the omnidirectional image **705** based on the panel model as illustrated in FIG. **19**. In a first step, the ECU **110** loads the pixel location from the omnidirectional image **705** (step **1905**). In a second step, the ECU **110** determines the pixel location on the panel based on the panel model (step **1910**). In a third step, the ECU **110** outputs the pixel location on the panel with respect to the local plane coordinate system (step **1915**). In one embodiment, the ECU **110** determines the pixel location using the following steps and equations. Given the pixel location in the omnidirectional image **705** x_f, transform the pixel location to the viewing sphere **710**:

$$X_C=g(x_f) \tag{43}$$

where g represents a function that maps an omnidirectional pixel location to a world location, and X_C is a point on the viewing sphere **710** defined with respect to the OCS. Map the location X_C to the local plane **805**.

$$X'_L=h_{s\to p}(X_C) \tag{44}$$

Rotate from the OCS coordinate system to local plane coordinate system.

$$X_L=R_{OCS}^{LTP}X'_L \tag{45}$$

Convert from the local plane **805** to a pixel location on the panel.

$$x = \left(\frac{X_P[1:2] - 1}{\Delta} \right) + 1 \quad (46)$$

where x represents the pixel location on the panel using ones based indexing.

In yet another example, which is illustrated in FIG. **20**, the ECU **110** determines a pixel location on the omnidirectional image **705** from a pixel location on the panel (x_f) based on the panel model. In a first step, the ECU **110** loads the pixel location on the panel (step **2005**). In a second step, the ECU **110** determines the corresponding pixel location on the omnidirectional image **705** based on the panel model (step **2010**). In a third step, the ECU **110** outputs the pixel location on the viewing sphere **710** with respect to the OCS (step **2015**). In one embodiment, the ECU **110** determines the pixel location based on the following steps and equations. Transform the pixel location to the local plane coordinate system:

$$X_L = \begin{bmatrix} (x-1)\Delta + \ell_P \\ 0 \end{bmatrix} \quad (47)$$

where

$$\ell_P = \begin{bmatrix} x_{lim}[1] \\ y_{lim}[1] \end{bmatrix}$$

represents a plane extent offset. Next, the world location on the local plane **805** is mapped to the viewing sphere **710** with the following computation:

$$X_C = h_{p \to s}(X_L) \quad (48)$$

where $h_{p \to s}$ is the local plane **805** to viewing sphere **710** function. Since, X_C is defined with respect to the OCS, the ECU **110** can convert it to the pixel location.

$$x_f = f(X_C) \quad (49)$$

where f represents a function that maps the world location defined with respect to the OCS to the pixel location on the omnidirectional image **705**.

In another example, which is illustrated in FIG. **21**, the ECU **110** determines a pixel location in a second panel based on a pixel location in a first panel. In a first step, the ECU **110** loads the pixel location from the first panel (step **2105**). In a second step, the ECU **110** determines the corresponding pixel position on the second panel based on a comparison between the first panel model for the first panel and the second panel model for the second panel (step **2010**). In a third step, the ECU **110** outputs the pixel position with reference to the second panel (step **2015**). In one embodiment, the ECU **110** determines the pixel location with reference to the second panel using the following steps and equations. The ECU **110** maps the pixel location from the first panel x into world coordinates with the expression:

$$X_C = \mathrm{PAN}_1 \cdot \mathrm{PixelToWorld}(x) \quad (50)$$

where $\mathrm{PAN}_1 \cdot \mathrm{PixelToWorld}$ denotes the pixel location to world location transform with respect to the first panel. Next, the ECU **110** normalizes to the viewing sphere **710**.

$$X'_C = \frac{X_C}{\|X_C\|} \quad (51)$$

The ECU **110** projects the point to the second panel.

$$X_L = \mathrm{PAN2} \cdot h_{s \to p}(X'_C) \quad (52)$$

where $\mathrm{PAN2} \cdot h_{s \to p}$ represents the viewing sphere **710** with respect to the second panel. The point on the second panel X_L is converted to the pixel location on the second panel.

$$x' = \left(\frac{X_L[1:2] - 1}{\Delta} \right) + 1 \quad (53)$$

where x' represents the pixel location with respect to the second panel using ones based indexing.

In yet another example illustrated in FIG. **22**, the ECU **110** determines a support function $h_{s \to p}$ as used in several examples herein. The ECU **110** determines a location of a point with respect to the local plane coordinate system from a point on the viewing sphere **710** defined with respect to the OCS. In a first step, the ECU **110** loads the coordinates of the point on the viewing sphere **710** (step **2205**). In a second step, the ECU **110** determines the coordinates of the point with respect to the local plane coordinate system (step **2210**). In a third step, the ECU **110** outputs the coordinates of the point with respect to the local plane coordinate system (step **2215**). In one embodiment, the ECU **110** uses the following functions to determine the coordinates of the point with respect to the local plane coordinate system.

point on plane	LTP.O
plane normal	LTP.Z
point on line	OCS.O = $[0\ 0\ 0]^T$
line direction	X_C

Denoting the solution as I_{OCS}, the ECU **110** transforms from OCS coordinates to local plane coordinates using the following relationship:

$$\begin{bmatrix} X_L \\ 1 \end{bmatrix} = M_{OCS}^{LTP} \begin{bmatrix} I_{OCS} \\ 1 \end{bmatrix} \quad (54)$$

where X_L is a point on the local plane **805** (e.g. the Z component is zero; $X_L[3]=0$)

In another example, which is illustrated in FIG. **23**, the ECU **110** determines an additional supporting function, $h_{p \to s}$, that transforms a point on the local plane **805** defined with respect to the local plane coordinate system to a location of a point on the viewing sphere **710** defined with respect to the OCS. In a first step, the ECU **110** loads the coordinates of the point on the viewing sphere **710** (step **2305**). In a second step, the ECU **110** determines the location of the point with respect to the OCS based on the panel model (step **2310**). In a third step, the ECU **110** outputs the location of the point with respect to the OCS (step **2315**). In one embodiment, the ECU **110** determines the coordinates of the point using the following steps and equations. Transform the point X_L defined with respect to the local plane coordinate system to the OCS.

$$\begin{bmatrix} X'_C \\ 1 \end{bmatrix} = M_{LTP}^{OCS} \begin{bmatrix} X_L \\ 1 \end{bmatrix} \quad (55)$$

The OCS point is mapped to the viewing sphere **710**.

$$X_C = \frac{X'_C}{\|X'_C\|} \quad (56)$$

It should be noted that these various functions may be performed by the ECU **110** in the process of operating the panel transform. These functions enable the ECU **110** to perform a wide variety of tasks relating to image transformations between an omnidirectional image model and a rectilinear image model.

For example, FIG. **24** illustrates fields of view for a vehicle **100** as the vehicle **100** is exiting from a parking space. The driver's natural vision is restricted by parked vehicles **2410** adjacent to the driver's parking space. Due to the parked vehicles **2410**, the driver has a narrow field of view **2415** until the vehicle **100** clears the rear of the parked vehicles **2410**. With the panel transform as illustrated in FIG. **1**, the driver can proceed to exit the parking space with greater awareness. As previously explained, the camera **105** provides an omnidirectional image **705** to the ECU **110**, and the ECU **110** transforms the omnidirectional image **705** into one or more rectilinear images for display to the driver. A field of view **2420** of the camera **105** extends perpendicular to the vehicle **100** to cover a wider area than the field of view **2415**.

In one embodiment illustrated in FIGS. **25**A through **25**D, the display **120** displays several images from the ECU **110**. In FIG. **25**A, the display displays an omnidirectional image **705** as captured by the camera **105**. In FIG. **25**B, the ECU **110** first converts the omnidirectional image **705** based on a parameter vector aligned along the optical origin **610** of the camera **105**. This image may be a default image sent by the ECU **110** on startup of the vehicle **100**. In this image, the far left and the far right sides of the omnidirectional image **705** are not displayed by the rectilinear image. In this embodiment, the far left and the far right sides are not displayed even when the image is displayed at a maximum horizontal and vertical angles of view. FIG. **25**C illustrates a rectilinear image when the parameter vector is orientated towards a first side of the vehicle **100**. Similarly, FIG. **25**D illustrates a rectilinear image when the parameter vector is orientated towards a second side of the vehicle **100**.

FIG. **26** illustrates an embodiment of the input interface **125**. In this embodiment, media keys **2605** are displayed that function as an input control for the ECU **110**. Starting from the default image, the driver may operate the input interface **125** to adjust the parameter vector, and thus the image to a region of interest to the driver. For example, if the driver plans on exiting a parking space by reversing towards a passenger side of the vehicle **100**, the driver may press a left arrow key to orientate the parameter vector to the passenger side. Then, the ECU **110** virtually changes the parameter vector further to the passenger side and thus allows the driver to view the image illustrated in FIG. **25**C without physically moving the camera **105**. It should be noted that the driver may also zoom in and zoom out the rectilinear image using the input interface **125**. Therefore, through the parameter vector, the camera **105**, even though fixed, may function as a virtual pan, zoom, and tilt camera.

Controls other than the input interface **125** may also adjust the parameter vector. These may be various types of driver-operated controls. For example, in one embodiment, the steering wheel **130** automatically adjusts the parameter vector to an angle based on the steering angle sensor **135**. In such an embodiment, when the driver turns the steering wheel **130** clockwise, the ECU **110** orientates the parameter vector towards the passenger side in anticipation of the vehicle **100** reversing towards the passenger side. This automatic adjustment may only be enabled when the vehicle is in the reverse gear. In addition, automatic adjustment may be used in combination with manual adjustment using input controls as described previously. In this case, the automatic control and the manual control may work in conjunction to orientate the parameter vector in real-time as requested by each control. In another embodiment, the manual control and the automatic control may be assigned priorities. For example, the automatic control may take precedence over the manual control when the vehicle is in reverse. Conversely, the manual control may take precedence over the automatic control anytime the driver selects a mode for manual operation. The priorities may be changed based on driver selection or held fixed based on predetermined safety criteria.

In other embodiments, the ECU **110** may perform image processing in support of additional functions either within the ECU **110** or in other vehicle systems. In particular, a hardware module or a software module may be included in the vehicle that relies on rectilinear images to perform their intended functions. The ECU **110** can perform the various transformations described herein to provide these modules with a rectilinear image model defined by the panel model. Therefore, third party imaging modules may be installed on the vehicle that interface with the ECU **110** even when these modules are not designed to operate with an omnidirectional camera. For example, modules that perform structure from motion algorithms and trained classifiers (e.g., pedestrian detection) based on rectilinear images may be implemented using the transforms. In other words, the panel model of the omnidirectional image **705** may be performed as a preprocessing step to transform the omnidirectional image **705** into a rectilinear image for direct use by preexisting algorithms.

Some preexisting algorithms require a large field of view, which may be provided by multiple rectilinear cameras. However, multiple cameras increase the cost of the vehicle. Advantageously, embodiments of the panel transform provide multiple rectilinear image feeds from a single omnidirectional camera **105** using multiple parameter vectors and multiple panel models as inputs to these multiple rectilinear image algorithms. For example, the panel transform may provide three 60 degree rectilinear views side-by-side on the display **120** based on a 180 degree omnidirectional image **705**. In this case, the ECU **110** would determine three parameter vectors to transform the omnidirectional image **705** and reconstruct a single image for display based on the three rectilinear images.

Thus, the invention provides, among other things, a panel transform in a vehicle that performs various functions with an omnidirectional image **705** captured from an omnidirectional camera **105** and outputs various values depending on the particular function being performed. Various features and advantages of the invention are set forth in the following claims.

What is claimed is:

1. A method of operating a vehicle imaging system, the method comprising:

receiving, at an electronic control unit, an omnidirectional image from a vehicle-based omnidirectional camera;

determining a first angular perspective vector;

generating a first rectilinear image orthogonal to the first angular perspective vector;

displaying the first rectilinear image to a driver of the vehicle;

receiving commands from a driver-operated, dual-purpose control, the driver-operated, dual-purpose control being configured to control a vehicle function in a first mode and the vehicle imaging system in a second mode,

adjusting the angular perspective vector based on the commands;

generating a second rectilinear image orthogonal to the adjusted angular perspective vector; and

displaying the second rectilinear image to the driver.

2. The method of claim **1**, wherein determining the angular perspective vector includes determining a yaw angle, a pitch angle, and a roll angle of the angular perspective vector in reference to an optical coordinate system defined with respect to the omnidirectional camera.

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

accessing an omnidirectional camera model representative of the omnidirectional image projected onto a unit sphere in the optical coordinate system,

wherein the angular perspective vector at least partially defines a local plane, and wherein the local plane is tangent to the unit sphere and orthogonal to the angular perspective vector.

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

determining a plane extent of the local plane, wherein the plane extent defines a boundary of the local plane based, at least in part, on the commands.

5. The method of claim **3**, the method further comprising:

determining a relationship between the local plane and the unit sphere, and

wherein generating the second rectilinear image is based on the determined relationship.

6. The method of claim **5**, wherein determining a relationship between the local plane and the unit sphere depends on the angular perspective vector.

7. The method of claim **1**, wherein the driver-operated, dual-purpose control includes buttons on a steering wheel.

8. The method of claim **1**, further comprising receiving an input from another driver-operated control and selecting the second mode based on the input from the another driver-operated control.

9. The method of claim **8**, wherein the another driver-operated control is a gear shift control.

10. A vehicle imaging system comprising:

an omnidirectional camera;

a display;

a driver-operated, dual-purpose control configured to control a vehicle function in a first mode and control a vehicle imaging system in a second mode; and

an electronic control unit configured to

receive an omnidirectional image from the omnidirectional camera,

determine a first angular perspective vector,

generate a first rectilinear image orthogonal to the first angular perspective vector,

send the first rectilinear image to the display,

enter into the second mode,

receive commands from the driver-operated, dual-purpose control,

adjust the angular perspective vector based on the commands,

generate a second rectilinear image orthogonal to the adjusted angular perspective vector, and

send the second rectilinear image to the display.

11. The vehicle imaging system of claim **10**, wherein an electronic control unit configured to determine the angular perspective vector also determines a yaw angle, a pitch angle, and a roll angle of the angular perspective vector in reference to an optical coordinate system defined with respect to the omnidirectional camera.

12. The vehicle imaging system of claim **11**, wherein the electronic control unit is further configured to:

access an omnidirectional camera model representative of the omnidirectional image projected onto a unit sphere in the optical coordinate system,

wherein the angular perspective vector at least partially defines a local plane, and wherein the local plane is tangent to the unit sphere and orthogonal to the angular perspective vector.

13. The vehicle imaging system of claim **10**, wherein the electronic control unit is further configured to:

determine a relationship between the local plane and the unit sphere, and

generate the second rectilinear image based on the determined relationship.

14. The vehicle imaging system of claim **13**, wherein the electronic control unit configured to determine a relationship between the local plane and the unit sphere determines the relationship based on the angular perspective vector.

15. The vehicle imaging system of claim **10**, wherein the driver-operated, dual-purpose control includes buttons on a steering wheel.

16. The vehicle imaging system of claim **10**, wherein the electronic control unit is further configured to enter into the second mode based on an input from another driver-operated control.

17. The vehicle imaging system of claim **16**, wherein the another driver-operated control is a gear shift control.

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