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(54) METHODS AND SYSTEMS FOR DETERMINING ALIGNMENT PARAMETERS OF A RADAR SENSOR

(57) A computer implemented method for determining alignment parameters of a radar sensor comprises the following steps carried out by computer hardware components: determining measurement data using the radar sensor, the measurement data comprising a range-rate measurement, an azimuth measurement, and an elevation measurement; determining a velocity of the radar sensor using a velocity sensor; and determining the misalignment parameters based on the measurement data and the velocity, the misalignment parameters comprising an azimuth misalignment, an elevation misalignment, and a roll misalignment.

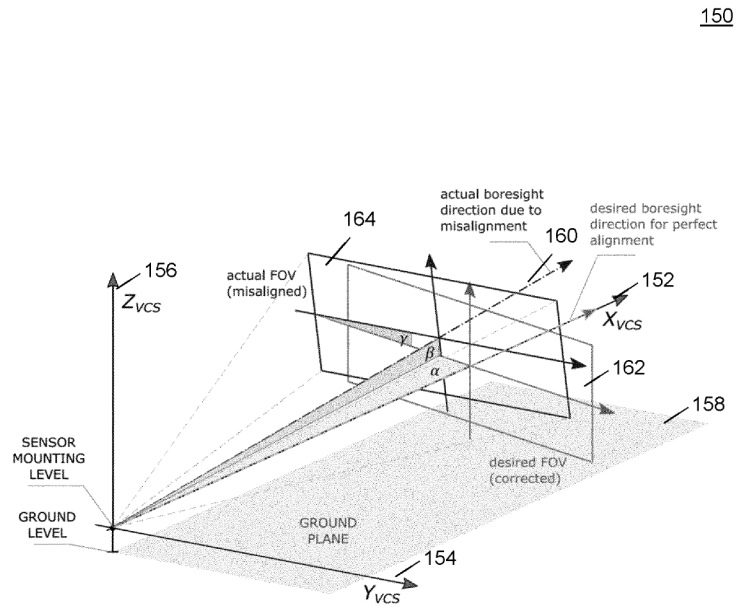

Fig. 1B

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Description

FIELD

[0001] The present disclosure relates to methods and systems for determining alignment parameters of a radar sensor.

BACKGROUND

[0002] Radar-sensors, for example in automotive applications, need to be aligned with the chassis of a host-vehicle so that the location of detected objects is accurately known. Alignment procedures performed when the host-vehicle is assembled are not able to compensate for pitch or elevation errors caused by heavy cargo and yaw, azimuth or roll errors caused by miss-alignment of the wheels or chassis of the host-vehicle which may cause 'crabbing' or 'dog-tracking' by the host-vehicle while traveling.

[0003] Accordingly, there is a need to provide for reliable determination of alignment parameters.

SUMMARY

[0004] The present disclosure provides a computer implemented method, a radar system, a computer system, a vehicle, and a non-transitory computer readable medium according to the independent claims. Embodiments are given in the subclaims, the description and the drawings.

[0005] In one aspect, the present disclosure is directed at a computer implemented method for determining alignment parameters of a radar sensor, the method comprising the following steps performed (in other words: carried out) by computer hardware components: determining measurement data using the radar sensor, the measurement data comprising a range-rate measurement, an azimuth measurement, and an elevation measurement; determining a velocity (in other words: speed) of the radar sensor using a velocity sensor; and determining the misalignment parameters based on the measurement data and the velocity, the misalignment parameters comprising an azimuth misalignment, an elevation misalignment, and a roll misalignment.

[0006] According to various embodiments, misalignment parameters may be determined by comparing a velocity determined by a velocity sensor (which may be independent from the radar sensor) and velocity information which is determined based on radar measurement data.

[0007] The measurements data may be related to the radar sensor, for example to a radar sensor mounted on a vehicle (for example at least partially autonomously driving vehicle, for example car), for example on the chassis of the vehicle. The velocity sensor may be external to the radar sensor; for example, the velocity sensor may be the velocity sensor of a vehicle, for example based on odometry measurements, gyroscope measurements, and/or acceleration measurements.

[0008] According to another aspect, the misalignment parameters further comprise a speed-scaling error.

[0009] It has been found that provided a three-axial-auto-alignment with speed-scaling-error estimation improves the detection quality of radar sensors.

[0010] According to another aspect, the computer implemented method further comprises the following step carried out by the computer hardware components: determining system parameters, the system parameters comprising at least one of a desired azimuth mounting angle, a desired elevation mounting angle, and a desired roll mounting angle; wherein the misalignment parameters are determined further based on the system parameters.

[0011] The system parameters may be set by the manufacturer of the system (for example vehicle) on which the radar sensor is provided. The system parameters may describe or define how the radar sensor is provided (for example mounted) in the vehicle.

[0012] According to another aspect, the measurement data is related to a plurality of objects external to the radar sensor. For example, measurement results related to at least three objects may be provided. For example, measurement results related to at least four objects may be provided. For example, measurement results related to at least five objects may be provided. The number of objects may be chosen so that the system for determining the misalignment parameters is at least not under-determined, for example so that the system is over-determined (i.e. more measurement results may be available than unknown misalignment parameters are to be determined; this may allow for implicit correction of measurement inaccuracies or measurement errors, for example by using regression methods to determine the misalignment parameters).

[0013] The objects may be provided outside a vehicle in which the radar sensor is provided.

[0014] According to another aspect, the plurality of objects are stationary. Thus, it may be considered known that the velocity determined by the velocity sensor is identical to the (relative) velocity of the stationary objects (relative to the radar sensor). This may be used for determining the misalignment parameters by determining the misalignment parameters so that the velocity determined based on the radar measurements is in agreement with the velocity determined by

the velocity sensor (for example so that the difference between the velocity determined based on the radar measurements is in agreement with the velocity determined by the velocity sensor is minimized).

[0015] According to another aspect, the misalignment parameters are determined based on an iterative method.

[0016] A closed-form solution to the determination of the misalignment parameters may not be available, or may be numerically instable. An iterative method may be used, starting from an initial estimate (or guess), for example with all misalignment parameters set to a default value (for example 0). The estimate values may be iteratively updated. The misalignment parameters may already be of reasonable accuracy after one iteration. Depending on the resources like time and computational power, more than one iteration may be performed. The iterations may continue until a pre-determined stop criterion is reached, for example a maximum time available for the determination of the misalignment parameters, or a pre-determined accuracy of the misalignment parameters (which may for example be determined based on how much (for example absolutely or relatively) the estimates for the misalignment parameters change from one iteration to the next iteration).

[0017] According to another aspect, the misalignment parameters are determined based on an optimization method.

[0018] The optimization method may optimize the misalignment parameters so that the difference between the velocity measured by the velocity sensor and the velocity which is determined based on the measurement data is minimized. The optimization method may determine the misalignment parameters from an overdetermined system (wherein more measurements, for example related to a plurality of objects, are available than would be required for a closed form determination of the misalignment parameters). The optimization method may use the Jacobian matrix, including partial derivatives of the modeled output with respect to the misalignment parameters.

[0019] According to another aspect, the misalignment parameters are determined based on a non-linear least squares regression method. According to another aspect, the misalignment parameters are determined based on an non-linear total least squares regression method.

[0020] According to another aspect, the misalignment parameters are determined based on filtering. For example, the misalignment parameters that have been determined based on the optimization or regression method may be subject to filtering, for example Kalman filtering, to further improve the misalignment parameters.

[0021] With the method according to various embodiments, the overall performance of the alignment may be improved, which may have a positive impact on the performance of further radar processing.

[0022] In another aspect, the present disclosure is directed at a computer implemented method for determining corrected measurement data, the method comprising the following steps carried out by computer hardware components: determining measurement data using a radar sensor; correcting the measurement data to obtain the corrected measurement data based on misalignment parameters determined according to the computer-implemented method described herein.

[0023] With the corrected measurement data, improved detection results may be achieved.

[0024] Based on the misalignment parameters, the control of the radar sensor (for example the area in which the radar sensor is to determine measurements) may be adjusted (for example to the desired area or desired field of view).

[0025] In another aspect, the present disclosure is directed at a computer system, said computer system comprising a plurality of computer hardware components configured to carry out several or all steps of the computer implemented method described herein. The computer system can be part of a vehicle.

[0026] The computer system may comprise a plurality of computer hardware components (for example a processor, for example processing unit or processing network, at least one memory, for example memory unit or memory network, and at least one non-transitory data storage). It will be understood that further computer hardware components may be provided and used for carrying out steps of the computer implemented method in the computer system. The non-transitory data storage and/or the memory unit may comprise a computer program for instructing the computer to perform several or all steps or aspects of the computer implemented method described herein, for example using the processing unit and the at least one memory unit.

[0027] In another aspect, the present disclosure is directed at a radar system comprising a radar sensor for which the misalignment parameters are determined according to the computer implemented method described herein.

[0028] In another aspect, the present disclosure is directed at a vehicle comprising the radar system described herein.

[0029] In another aspect, the present disclosure is directed at a non-transitory computer readable medium comprising instructions for carrying out several or all steps or aspects of the computer implemented method described herein. The computer readable medium may be configured as: an optical medium, such as a compact disc (CD) or a digital versatile disk (DVD); a magnetic medium, such as a hard disk drive (HDD); a solid state drive (SSD); a read only memory (ROM), such as a flash memory; or the like. Furthermore, the computer readable medium may be configured as a data storage that is accessible via a data connection, such as an internet connection. The computer readable medium may, for example, be an online data repository or a cloud storage.

[0030] The present disclosure is also directed at a computer program for instructing a computer to perform several or all steps or aspects of the computer implemented method described herein.

DRAWINGS

[0031] Exemplary embodiments and functions of the present disclosure are described herein in conjunction with the following drawings, showing schematically:

Fig. 1A an illustration of a radar field-of-view when misaligned in azimuth and elevation;

Fig. 1B an illustration of a three-dimensional misalignment in azimuth, elevation, and roll;

Fig. 2 a flow diagram illustrating an overview of methods for determining alignment parameters according to various embodiments;

Fig. 3 an illustration of a radar field-of-view after introduction of roll misalignment;

Fig. 4 an illustration of a radar field-of-view and a compensated field-of-view according to various embodiments;

Fig. 5 a diagram illustrating azimuth alignment error distribution according to various embodiments;

Fig. 6 a diagram illustrating elevation alignment error distribution according to various embodiments;

Fig. 7 a diagram illustrating roll alignment error distribution according to various embodiments;

Fig. 8 a flow diagram illustrating a method for determining alignment parameters of a radar sensor according to various embodiments;

Fig. 9 an alignment parameter estimation system according to various embodiments; and

Fig. 10 a computer system with a plurality of computer hardware components configured to carry out steps of a computer implemented method for determining alignment parameters of a radar sensor according to various embodiments.

DETAILED DESCRIPTION

[0032] Radar alignment is a process of determining the angular misalignment of radar facing direction. Correction of those mounting errors may be crucial for proper operation of radar based tracking methods and most of the feature functions that operate on detections or tracked objects provided by a radar sensor. Two main classes of methods/approaches aimed at solving misalignment problem are:

1) static alignment methods, which may also be called factory alignment, due to the reason that they require specialized equipment to perform the calibration process; most commonly used static methods use corner reflectors, Doppler generators, or steel plates;

2) dynamic alignment methods, which may also be called auto-alignment since they may not require any external (additional) equipment (devices) for the process. The radar sensor is correcting its facing angles based on observation of the environment while the car is moving (i.e. driving).

[0033] Fig. 1A and Fig. 1B shows illustrations 100 and 150 of misalignment and radar field-of-view relationship.

[0034] Fig. 1A shows an illustration 100 of a radar field-of-view 110 when misaligned in azimuth (along a horizontal line 102) and elevation (along a vertical split line 104 at the front of the vehicle, which corresponds to 0 deg). The ideal (or desired or assumed) facing angle 106 is different from the real (or actual) facing angle 108, so that a misalignment 112 is present.

[0035] Fig. 1B shows an illustration 150 of a three-dimensional misalignment in azimuth (α), elevation (β), and roll (γ). Coordinates axis are illustrated in the vehicle coordinate system (VCS), i.e. X_{VCS} 152, Y_{VCS} 154, and Z_{VCS} 156. The ground plane 158 is illustrated. The radar sensor may be mounted above ground plane 158 at the origin of the vehicle coordinate system. The desired boresight direction for perfect alignment would coincide with X_{VCS} 152. However, the actual boresight direction 160 is different from X_{VCS} 152 due to the misalignment, and the difference between the actual boresight direction 160 and X_{VCS} 152 may be described by the three-dimensional misalignment in azimuth (α), elevation (β), and roll (γ). Due to the misalignment, the desired FOV 162 (field of view) may be different from the actual FOV 164.

However, the desired FOV 162 may be obtained by correction based on misalignment parameters based on the actual FOV 164.

[0036] To calculate the misalignment in case of a misalignment in azimuth and elevation (disregarding a possible misalignment in roll), the range rate equation of stationary detections may be used. It may be derived from the projection of the negative vehicle velocity vector to the vector of distance, which forms the equation below:

$$\dot{r} = -V_X \cos\alpha_{VCS} \cos\beta_{VCS} - V_Y \sin\alpha_{VCS} \cos\beta_{VCS} - V_Z \sin\beta_{VCS} \quad (1)$$

where:

- $\dot{r}$ is the range rate (Doppler velocity of stationary detection);
- V_X is the longitudinal velocity of the vehicle (which may be a vector facing forward from vehicle, parallel to the ground plane; V_X may be the length of that vector);
- V_Y is the lateral velocity of the vehicle (which may be a vector facing left side of vehicle, parallel to the ground plane; V_Y may be the length of that vector);
- V_Z is the vertical velocity of the vehicle (which may be a vector facing ground, perpendicular to the ground plane; V_Z may be the length of that vector);
- α_{VCS} is the azimuth measurement of detection aligned to vehicle coordinate system (wherein the 0 [deg] angle may be defined as facing the same direction as the front of the vehicle on which the radar sensor is mounted); and
- β_{VCS} is the elevation measurement of detection aligned to vehicle coordinate system.

[0037] VCS aligned measurement angles may be decomposed into sensor mounting angles, sensor detection measurement angles as well as sensor mounting misalignment angles:

$$\alpha_{VCS} = \alpha_{SCS} + \alpha_B + \alpha_M \quad (2)$$

$$\beta_{VCS} = \beta_{SCS} + \beta_B + \beta_M \quad (3)$$

where:

- α_{SCS} is the azimuth measurement of detection in sensor coordinate system (SCS);
- α_B is the desired azimuth mounting angle;
- α_M is the desired azimuth misalignment;
- β_{SCS} is the elevation measurement of detection in sensor coordinate system;
- β_B is the desired elevation mounting angle; and
- β_M is the elevation misalignment.

[0038] Further expanding the equation with speed correction factor V_c (which may also be referred to as (vehicle) speed-scaling-error or speed compensation factor) leads to:

$$V_X = \frac{V_{Xm}}{1+V_c} \quad (4)$$

$$V_Y = \frac{V_{Ym}}{1+V_c} \quad (5)$$

$$V_Z = \frac{V_{Zm}}{1+V_c} \quad (6)$$

where:

- V_{Xm} is the measured longitudinal velocity of vehicle;

- V_{Ym} is the measured lateral velocity of vehicle;
- V_{Zm} is the measured vertical velocity of the vehicle; and
- V_c is the speed-scaling-error.

[0039] An equation may be created which may be used to find unknown parameters (B), based on measurements (X), known constants (C) and equation result (Y) as follows:

$$f(C\{\alpha_B, \beta_B\}, X\{\alpha_{SCS}, \beta_{SCS}, V_{Xm}, V_{Ym}, V_{Zm}\}, B\{\alpha_M, \beta_M, V_c\}) = Y\{\dot{r}\} \quad (7)$$

[0040] Various methods, such as iterative non-linear least squares regression or error-in-variables methods, may be used to determine the unknown parameters. The parameters found by these methods may then further be refined by filtering in time methods such as Kalman filter.

[0041] Fig. 2 shows a flow diagram 200 illustrating an overview of methods for determining alignment parameters according to various embodiments (either not taking into account a misalignment in roll angle, or taking into account a misalignment in roll angle, like will be described in more detail below). At 202, data acquisition may be carried out, which may include stationary detections, vehicle velocities, and radar information. At 204, regression may be carried out, for example including estimation of azimuth misalignment, estimation of elevation misalignment, estimation of roll misalignment (as will be described in more detail below), and estimation of speed-scaling error. At 206, filtering (for example using a Kalman filter) may be provided.

[0042] Significant roll misalignment angle of the sensor (desired sensor roll is usually zero) can greatly impact the azimuth and elevation measurements, because it reduces radar field of view as shown below.

[0043] Roll angle misalignment may influence the azimuth-elevation misalignment calculation itself.

[0044] Fig. 3 shows an illustration 300 of a radar field-of-view after introduction of roll misalignment, similar to what is shown in Fig. 1A (wherein in Fig. 1A no roll misalignment is illustrated). Illustration 302 in the left portion of Fig. 3 shows an illustration from the ground perspective, and illustration 304 in the right portion of Fig. 3 shows an illustration from the sensor perspective.

[0045] As can be seen from Fig. 3, if the roll misalignment would not be taken into account, the azimuth misalignment may be taken as 0 (zero) or close to 0, and the elevation misalignment may be estimated to be greater than the correct value of the elevation misalignment, due to the fact that the ideal facing angle is exactly below the reported facing angle as seen by the radar sensor. This may result in finding wrong misalignment parameters, for example zero azimuth misalignment and too high elevation misalignment value.

[0046] The impact of the roll angle misalignment may be almost unobservable for small angles (for example less than 1 [deg]), and may be growing exponentially with the roll, introducing highest error at the corners of field-of-view. At a 30 [deg] radar roll (i.e. a misalignment of the radar sensor in roll angle of 30 deg), as is illustrated in Fig. 3 and Fig. 4, the error is reducing the field of view of radar by half (the sensor may observe ground in near vicinity of front of the vehicle, and the sky above on the opposite side of FOV; however, both the ground and the sky regions are irrelevant from the active safety methods perspective). At the same time, a significant part of important information about objects located approximately 0.5 m above the ground is missed. Furthermore, an undetected roll angle misalignment may make the azimuth and elevation misalignment angles unreliable. For example, an object at 60 deg azimuth and 5 deg elevation under influence of 5 deg sensor roll misalignment will be reported at azimuth 60.20 deg and -0.2484 deg elevation.

[0047] The radar roll angle misalignment may be determined by extending the range rate equation, which makes estimation of the roll angle possible. The equation may further improve estimation of yaw and pitch angle misalignments. After the estimation of 3 angle misalignments (yaw, pitch, roll) the measured detections may be corrected to represent detections in vehicle coordinate system or in extreme misalignment the estimated value may trigger an alert which will stop the execution of further radar functions.

[0048] The range rate equation (1) may be used together with equations (2) and (3), which may be extended with the roll angle influence, what leads to following equations:

$$\alpha_{VCS} = \alpha_{SCS}{}' + \alpha_B + \alpha_M \quad (8)$$

$$\beta_{VCS} = \beta_{SCS}{}' + \beta_B + \beta_M \quad (9)$$

$$\alpha'_{SCS} = \alpha_{SCS} \cos(\gamma_M + \gamma_B) - \beta_{SCS} \sin(\gamma_M + \gamma_B) \quad (10)$$

$$\beta'_{SCS} = \alpha_{SCS}\sin(\gamma_M + \gamma_B) + \beta_{SCS}\cos(\gamma_M + \gamma_B) \quad (11)$$

where:

- α'_{SCS} is the azimuth measurement corrected by roll misalignment in sensor coordinate system;
- β'_{SCS} is the elevation measurement corrected by roll misalignment in sensor coordinate system;
- γ_M is the roll misalignment; and
- γ_B is the roll ideal mounting position (which may usually be 0 deg or 180 deg).

[0049] Therefore, α'_{SCS} and β'_{SCS} may be visualized as detections with the same distance from radar center of view (0, 0), but rotated (aligned) w.r.t. horizon line (assuming desired roll mounting angle of 0 [deg]), forming a 'compensated field of view' as shown on Fig. 4.

[0050] Fig. 4 shows an illustration 400 of a radar field-of-view 110 and a compensated field-of-view 402 according to various embodiments. Various portions of Fig. 4 are similar or identical to portions of Fig. 1A, so that the same reference signs may be used and duplicate description may be omitted.

[0051] After substitution of eqns. (8) and (9) (α' and β'_{SCS}) to eqns. (2) (3) for α_{SCS} and β_{SCS}, respectively, the following equations may be obtained:

$$\alpha_{VCS} = \alpha_{SCS}\cos(\gamma_M + \gamma_B) - \beta_{SCS}\sin(\gamma_M + \gamma_B) + \alpha_B + \alpha_M \quad (12)$$

$$\beta_{VCS} = \alpha_{SCS}\sin(\gamma_M + \gamma_B) + \beta_{SCS}\cos(\gamma_M + \gamma_B) + \beta_B + \beta_M \quad (13)$$

[0052] This change modifies the general model in equation (7) to:

$$f(C\{\alpha_B, \beta_B, \gamma_B\}, X\{\alpha_{SCS}, \beta_{SCS}, V_{Xm}, V_{Ym}, V_{Zm}\}, B\{\alpha_M, \beta_M, \gamma_M, V_c\}) = Y\{\dot{r}\} \quad (14)$$

[0053] The general form of this model can be derived from range rate equation (1)

$$\begin{aligned}\dot{r} = &-\frac{V_{Xm}}{1+V_c}\cos(\alpha_{SCS}\cos(\gamma_M + \gamma_B) - \beta_{SCS}\sin(\gamma_M + \gamma_B) + \alpha_B + \alpha_M) \cdot \\ &\cos(\alpha_{SCS}\sin(\gamma_M + \gamma_B) + \beta_{SCS}\cos(\gamma_M + \gamma_B) + \beta_B + \beta_M) - \\ &\frac{V_{Ym}}{1+V_c}\sin(\alpha_{SCS}\cos(\gamma_M + \gamma_B) - \beta_{SCS}\sin(\gamma_M + \gamma_B) + \alpha_B + \alpha_M) \cdot \\ &\cos(\alpha_{SCS}\sin(\gamma_M + \gamma_B) + \beta_{SCS}\cos(\gamma_M + \gamma_B) + \beta_B + \beta_M) - \\ &\frac{V_{Zm}}{1+V_c}\sin(\alpha_{SCS}\sin(\gamma_M + \gamma_B) + \beta_{SCS}\cos(\gamma_M + \gamma_B) + \beta_B + \beta_M)\end{aligned} \quad (15)$$

[0054] Eq. (13) can be simplified with the assumption of the vehicle moving only in forward direction (V_{Ym} and V_{Zm} equal to 0) and elevation and roll desired mounting angles 0 [deg], to get the following form:

$$\dot{r} = -\frac{V_{Xm}}{1+V_c}\cos(\alpha_{SCS}cos\gamma_M - \beta_{SCS}\sin\gamma_M + \alpha_B + \alpha_M) \cdot \cos(\alpha_{SCS}\sin\gamma_M + \beta_{SCS}\cos\gamma_M + \beta_M) \quad (16)$$

[0055] Equation (16) may be used to compose (create) a overdetermined system of equations which can be solved by various methods to find parameters of interest i.e. misalignment angles and speed compensation factor. In an example, equation (14) may be used as a model for non-linear least square regression. For example, the model may be iterative, which means that the method will iterate over the same dataset containing data from one time instance to converge to the solution of non-linear equation in multiple steps defined by linearization of the model around its operating point:

$$(J^T \cdot J)\,\Delta B = J^T \cdot \Delta Y \quad (17)$$

[0056] The matrix equation (17) can be transformed to:

$$\Delta B = (J^T \cdot J)^{-1} \cdot J^T \cdot \Delta Y \tag{18}$$

where:

- ΔB is the update of parameters value in a single iteration (single step in a solution space);
- J are the partial derivatives of model function over the parameters (which may be referred to as Jacobian matrix); and
- ΔY is the difference between the measured output of the system and model output:

$$\Delta Y = \begin{bmatrix} \dot{r}_1 - f_1 \\ \vdots \\ \dot{r}_n - f_n \end{bmatrix} \tag{19}$$

[0057] The Jacobian matrix may take the following form:

$$J = \begin{bmatrix} \frac{\partial f_1}{\partial V_c} & \frac{\partial f_1}{\partial \alpha_M} & \frac{\partial f_1}{\partial \beta_M} & \frac{\partial f_1}{\partial \gamma_M} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{\partial f_n}{\partial V_c} & \frac{\partial f_n}{\partial \alpha_M} & \frac{\partial f_n}{\partial \beta_M} & \frac{\partial f_n}{\partial \gamma_M} \end{bmatrix} \tag{20}$$

where:

$$\frac{\partial f_i}{\partial V_c} = \frac{V_{Xm}}{(1+V_c)^2} \cos(\alpha_{SCS}^i cos\gamma_M - \beta_{SCS}^i \sin\gamma_M + \alpha_B + \alpha_M) \cdot \cos(\alpha_{SCS}^i \sin\gamma_M + \beta_{SCS}^i \cos\gamma_M + \beta_M) \tag{21}$$

$$\frac{\partial f_i}{\partial \alpha_M} = \frac{V_{Xm}}{1+V_c} \sin(\alpha_{SCS}^i cos\gamma_M - \beta_{SCS}^i \sin\gamma_M + \alpha_B + \alpha_M) \cdot \cos(\alpha_{SCS}^i \sin\gamma_M + \beta_{SCS}^i \cos\gamma_M + \beta_M) \tag{22}$$

$$\frac{\partial f_i}{\partial \beta_M} = \frac{V_{Xm}}{1+V_c} \cos(\alpha_{SCS}^i cos\gamma_M - \beta_{SCS}^i \sin\gamma_M + \alpha_B + \alpha_M) \cdot \sin(\alpha_{SCS}^i \sin\gamma_M + \beta_{SCS}^i \cos\gamma_M + \beta_M) \tag{23}$$

$$\frac{\partial f_i}{\partial \gamma_M} = \frac{V_{Xm}}{1+V_c}\cos(\alpha^i_{SCS}cos\gamma_M - \beta^i_{SCS}\sin\gamma_M + \alpha_B + \alpha_M)\cdot\sin(\alpha^i_{SCS}\sin\gamma_M + \beta^i_{SCS}\cos\gamma_M + \beta_M)\cdot(\alpha^i_{SCS}cos\gamma_M - \beta^i_{SCS}\sin\gamma_M) - \frac{V_{Xm}}{1+V_c}\sin(\alpha^i_{SCS}cos\gamma_M - \beta^i_{SCS}\sin\gamma_M + \alpha_B + \alpha_M)\cdot\cos(\alpha^i_{SCS}\sin\gamma_M + \beta^i_{SCS}\cos\gamma_M + \beta_M)\cdot(\alpha^i_{SCS}sin\gamma_M + \beta^i_{SCS}\cos\gamma_M) \quad (24)$$

[0058] The non-linear regression model described by equations (18) to (24) may be solved after assuming initial values of parameters:

$$B_0 = \begin{cases} \begin{bmatrix}0\\0\\0\\0\end{bmatrix} for\ m = 0 \\ \begin{bmatrix}V_{c\ m-1}\\ \alpha_{M\ m-1}\\ \beta_{M\ m-1}\\ \gamma_{M\ m-1}\end{bmatrix} for\ m > 1 \end{cases} \quad (25)$$

where m is the number of successful alignment cycles (radar cycles). In other words, a misalignment of 0 in the azimuth, elevation and roll angles and in the speed-correction factor may be assumed as the starting point for the first iteration, and the results of the previous iteration may be used as starting point for the next iteration.

[0059] Therefore, equation (26) may update model parameter values with values at i-th iteration:

$$B_i = B_{i-1} + \Delta B_i \quad (26)$$

[0060] B_i may converge to real speed-scaling-error and misalignment angles at infinite number of iterations (or as iteration number approaches infinity):

$$\lim_{i\to\infty} B_i = \begin{bmatrix}V_c\\ \alpha_M\\ \beta_M\\ \gamma_M\end{bmatrix} \quad (27)$$

[0061] The method according to various embodiments provides alignment parameters also for the roll axis, which accurately describes the physical model.

[0062] Fig. 5, Fig. 6 and Fig. 7 illustrate the performance of methods according to various embodiments over simulated data for random (nonzero) misalignments of all mounting angles i.e. azimuth, elevation and roll. The following simulation parameters were used:

- number of test cases (samples): 500 000 (same inputs for each method);
- misalignments (azimuth, elevation and roll): pseudorandom values drawn from uniform distribution on interval [-5:5] deg;
- azimuth boresight pseudorandom value drawn from uniform distribution on interval [-180; 180] deg;
- vehicle moving in a straight line (X_{VCS} direction);
- minimum vehicle speed: 11 m/s;
- number of detections: 64;
- azimuth Gaussian zero mean noise: Standard deviation 0.3 deg;

- elevation Gaussian zero mean noise: Standard deviation 1 deg ;
- range rate Gaussian zero mean noise: Standard deviation 0.03 m/s;
- vehicle velocity Gaussian zero mean noise in 3-axis : Standard deviation 0.2 m/s.

[0063] The result of only a single iteration (first iteration) of each of compared method is shown in each of Fig. 5, Fig. 6, and Fig. 7. NL-LS in the method name may stand for non-linear least squares regression used to find the solution, and NL-TLS may stand for non-linear total least squares regression. A 2-axial alignment with no roll estimation is shown for comparison purposes.

[0064] Fig. 5 shows a diagram 500 illustrating azimuth alignment error distribution according to various embodiments. The deviation angle is illustrated over a horizontal axis 502. The numbers of samples is illustrated over a vertical axis 504. The results for a 2 axial alignment are illustrated by curve 506. The results for a 3 axial alignment NL-LS method according to various embodiments are illustrated by curve 508. The results for a 3 axial alignment NL-TLS method according to various embodiments are illustrated by curve 510.

[0065] Fig. 6 shows a diagram 600 illustrating elevation alignment error distribution according to various embodiments. The deviation angle is illustrated over a horizontal axis 602. The numbers of samples is illustrated over a vertical axis 604. The results for a 2 axial alignment are illustrated by curve 606. The results for a 3 axial alignment NL-LS method according to various embodiments are illustrated by curve 608. The results for a 3 axial alignment NL-TLS method according to various embodiments are illustrated by curve 610.

[0066] Fig. 7 shows a diagram 700 illustrating roll alignment error distribution according to various embodiments. The deviation angle is illustrated over a horizontal axis 702. The numbers of samples is illustrated over a vertical axis 704. The results for a 3 axial alignment NL-LS method according to various embodiments are illustrated by curve 706. The results for a 3 axial alignment NL-TLS method according to various embodiments are illustrated by curve 708.

[0067] As shown in Fig. 5 and Fig. 6, even one-time-instance-based (non-iterative) results are much better in case of azimuth and elevation misalignment estimation with 3-axial alignment compared to a 2-axial alignment.

[0068] Fig. 7 shows the error distribution of roll angle alignment, in this case 2 axial alignment is not available as it doesn't return the roll angle estimation.

[0069] Fig. 8 shows a flow diagram 800 illustrating a method for determining alignment parameters of a radar sensor according to various embodiments. At 802, measurement data may be determined using the radar sensor, wherein the measurement data may include a range-rate measurement, an azimuth measurement, and an elevation measurement. At 804, a velocity of the radar sensor may be determined using a velocity sensor. At 806, the misalignment parameters may be determined based on the measurement data and the velocity, wherein the misalignment parameters may include an azimuth misalignment, an elevation misalignment, and a roll misalignment.

[0070] According to various embodiments, the misalignment parameters may further include a speed-scaling error.

[0071] According to various embodiments, system parameters may be determined, wherein the system parameters may include at least one of a desired azimuth mounting angle, a desired elevation mounting angle, and a desired roll mounting angle. The misalignment parameters may be determined further based on the system parameters.

[0072] According to various embodiments, the measurement data may be related to a plurality of objects external to the radar sensor.

[0073] According to various embodiments, the plurality of objects may be stationary.

[0074] According to various embodiments, the misalignment parameters may be determined based on an iterative method.

[0075] According to various embodiments, the misalignment parameters may be determined based on an optimization method.

[0076] According to various embodiments, the misalignment parameters may be determined based on a non-linear least squares regression method.

[0077] According to various embodiments, the misalignment parameters may be determined based on an non-linear total least squares regression method. According to various embodiments, the misalignment parameters may be determined based on filtering.

[0078] Each of the steps 802, 804, 806 and the further steps described above may be performed by computer hardware components.

[0079] Fig. 9 shows an alignment parameter estimation system 900 according to various embodiments. The alignment parameter estimation system 900 may include a measurement data determination circuit 902, a velocity determination circuit 904, and a misalignment parameters determination circuit 906.

[0080] The measurement data determination circuit 902 may be configured to determine measurement data using a radar sensor, the measurement data comprising a range-rate measurement, an azimuth measurement, and an elevation measurement. The radar sensor may be a part of the measurement data determination circuit 902, or may be provided external to the measurement data determination circuit 902.

[0081] The velocity determination circuit 904 may be configured to determine a velocity of the radar sensor using a

velocity sensor. The velocity sensor may be a part of the velocity determination circuit 904, or may be provided external to the velocity determination circuit 904.

[0082] The misalignment parameters determination circuit 906 may be configured to determine misalignment parameters of the radar sensor based on the measurement data and the velocity, the misalignment parameters comprising an azimuth misalignment, an elevation misalignment, and a roll misalignment

[0083] The measurement data determination circuit 902, the velocity determination circuit 904, and the misalignment parameters determination circuit 906 may be coupled with each other, e.g. via an electrical connection 908, such as e.g. a cable or a computer bus or via any other suitable electrical connection to exchange electrical signals.

[0084] A "circuit" may be understood as any kind of a logic implementing entity, which may be special purpose circuitry or a processor executing a program stored in a memory, firmware, or any combination thereof.

[0085] Fig. 10 shows a computer system 1000 with a plurality of computer hardware components configured to carry out steps of a computer implemented method for determining alignment parameters of a radar sensor according to various embodiments. The computer system 1000 may include a processor 1002, a memory 1004, and a non-transitory data storage 1006. A radar sensor 1008 and/or a velocity sensor 1010 may be provided as part of the computer system 1000 (like illustrated in Fig. 10), or may be provided external to the computer system 1000.

[0086] The processor 1002 may carry out instructions provided in the memory 1004. The non-transitory data storage 1006 may store a computer program, including the instructions that may be transferred to the memory 1004 and then executed by the processor 1002. The radar sensor 1008 may be used for determining measurement data as described above. The velocity sensor 1010 may be used to determine the velocity as described above.

[0087] The processor 1002, the memory 1004, and the non-transitory data storage 1006 may be coupled with each other, e.g. via an electrical connection 1012, such as e.g. a cable or a computer bus or via any other suitable electrical connection to exchange electrical signals. The radar sensor 1008 and/or the velocity sensor 1010 may be coupled to the computer system 1000, for example via an external interface, or may be provided as parts of the computer system (in other words: internal to the computer system, for example coupled via the electrical connection 1012).

[0088] The terms "coupling" or "connection" are intended to include a direct "coupling" (for example via a physical link) or direct "connection" as well as an indirect "coupling" or indirect "connection" (for example via a logical link), respectively.

[0089] It will be understood that what has been described for one of the methods above may analogously hold true for the alignment parameter estimation system 900 and/or for the computer system 1000.

Reference numeral list

[0090]

100	illustration of a radar field-of-view when misaligned in azimuth and elevation
102	horizontal line
104	vertical split line
106	ideal facing angle
108	real facing angle
110	radar field-of-view
112	misalignment
150	illustration of a three-dimensional misalignment in azimuth, elevation, and roll
152	x axis
154	y axis
156	z axis
158	ground plane
160	actual boresight direction
162	desired field of view
164	actual field of view
200	flow diagram illustrating an overview of methods for determining alignment parameters according to various embodiments
202	data acquisition
204	regression
206	filtering
300	illustration of a radar field-of-view after introduction of roll misalignment
302	illustration from the ground perspective

304 illustration from the sensor perspective

400 illustration of a radar field-of-view and a compensated field-of-view according to various embodiments
402 compensated field-of-view
500 diagram illustrating azimuth alignment error distribution according to various embodiments
502 horizontal axis
504 vertical axis
506 curve illustrating results for a 2 axial alignment
508 curve illustrating results for a 3 axial alignment NL-LS method according to various embodiments
510 curve illustrating results for a 3 axial alignment NL-TLS method according to various embodiments

600 diagram illustrating elevation alignment error distribution according to various embodiments
602 horizontal axis
604 vertical axis
606 curve illustrating results for a 2 axial alignment
608 curve illustrating results for a 3 axial alignment NL-LS method according to various embodiments
610 curve illustrating results for a 3 axial alignment NL-TLS method according to various embodiments

700 diagram illustrating roll alignment error distribution according to various embodiments
702 horizontal axis
704 vertical axis
706 curve illustrating results for a 3 axial alignment NL-LS method according to various embodiments
708 curve illustrating results for a 3 axial alignment NL-TLS method according to various embodiments

800 flow diagram illustrating a method for determining alignment parameters of a radar sensor according to various embodiments
802 step of determining measurement data using the radar sensor
804 step of determining a velocity of the radar sensor using a velocity sensor
806 step of determining the misalignment parameters based on the measurement data and the velocity

900 alignment parameter estimation system according to various embodiments
902 measurement data determination circuit
904 velocity determination circuit
906 misalignment parameters determination circuit
908 connection

1000 computer system according to various embodiments
1002 processor
1004 memory
1006 non-transitory data storage
1008 radar sensor
1010 velocity sensor
1012 connection

Claims

1. Computer implemented method for determining alignment parameters of a radar sensor,
the method comprising the following steps carried out by computer hardware components:

- determining measurement data using the radar sensor, the measurement data comprising a range-rate measurement, an azimuth measurement, and an elevation measurement;
- determining a velocity of the radar sensor using a velocity sensor; and
- determining the misalignment parameters based on the measurement data and the velocity, the misalignment parameters comprising an azimuth misalignment, an elevation misalignment, and a roll misalignment.

2. The computer implemented method of claim 1,
wherein the misalignment parameters further comprise a speed-scaling error.

3. The computer implemented method of at least one of claims 1 or 2, further comprising the following step carried out by the computer hardware components:

   determining system parameters, the system parameters comprising at least one of a desired azimuth mounting angle, a desired elevation mounting angle, and a desired roll mounting angle;
   wherein the misalignment parameters are determined further based on the system parameters.

4. The computer implemented method of at least one of claims 1 to 3, wherein the measurement data is related to a plurality of objects external to the radar sensor.

5. The computer implemented method of claim 4,
   wherein the plurality of objects are stationary.

6. The computer implemented method of at least one of claims 1 to 5, wherein the misalignment parameters are determined based on an iterative method.

7. The computer implemented method of at least one of claims 1 to 6, wherein the misalignment parameters are determined based on an optimization method.

8. The computer implemented method of at least one of claims 1 to 7, wherein the misalignment parameters are determined based on a non-linear least squares regression method.

9. The computer implemented method of at least one of claims 1 to 8, wherein the misalignment parameters are determined based on an non-linear total least squares regression method.

10. The computer implemented method of at least one of claims 1 to 9, wherein the misalignment parameters are determined based on filtering.

11. Computer implemented method for determining corrected measurement data,
    the method comprising the following steps carried out by computer hardware components:

    determining measurement data using a radar sensor;
    correcting the measurement data to obtain the corrected measurement data based on misalignment parameters determined according to the computer-implemented method of at least one of claims 1 to 10.

12. Computer system, the computer system comprising a plurality of computer hardware components configured to carry out steps of the computer implemented method of at least one of claims 1 to 11.

13. A radar system comprising a radar sensor for which the misalignment parameters are determined according to the computer implemented method of at least one of claims 1 to 11.

14. A vehicle comprising the radar system of claim 13.

15. Non-transitory computer readable medium comprising instructions for carrying out the computer implemented method of at least one of claims 1 to 11.

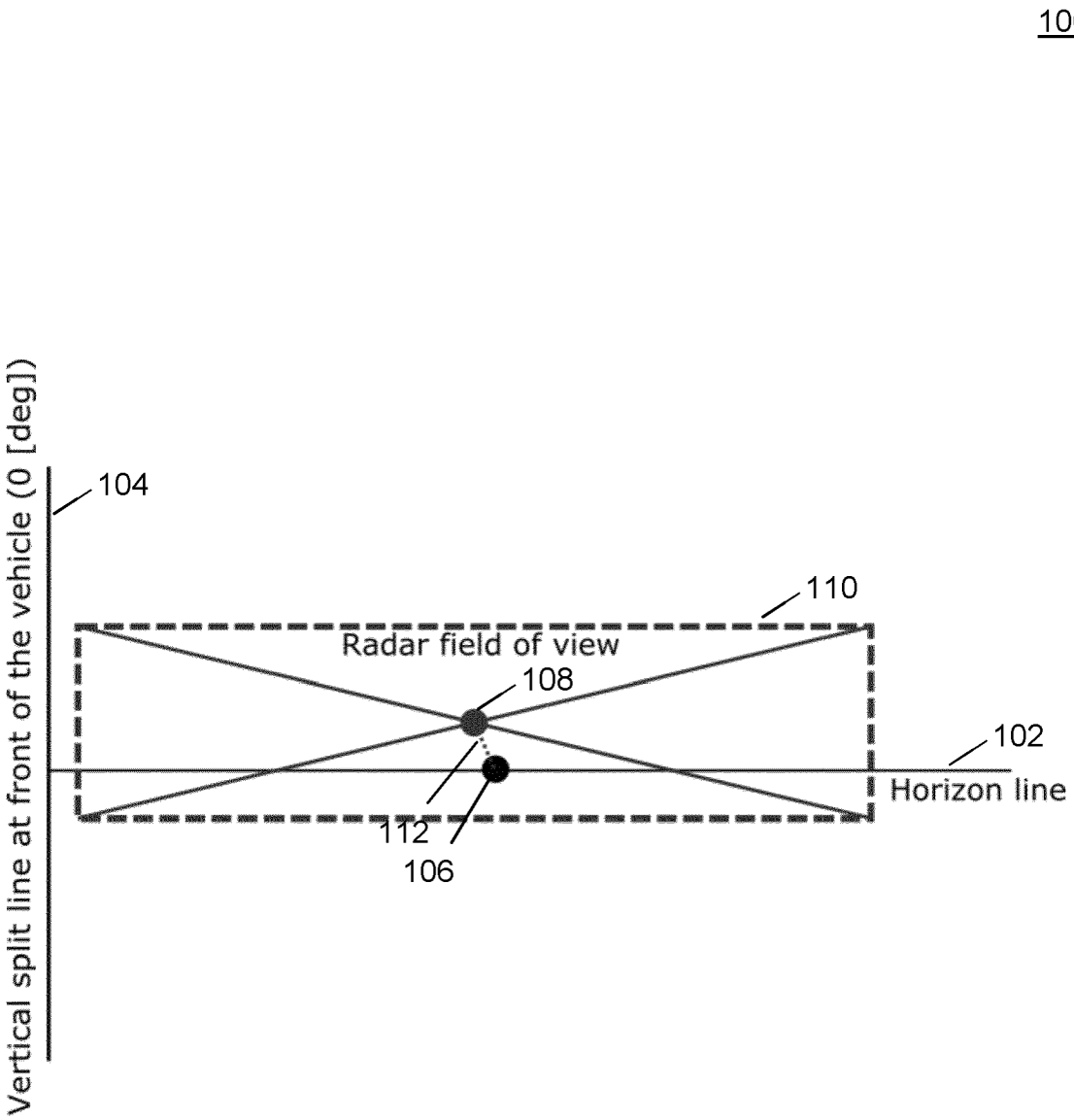
100
Vertical split line at front of the vehicle (0 [deg])
104
110
Radar field of view
108
102
Horizon line
112
106

Fig. 1A

150

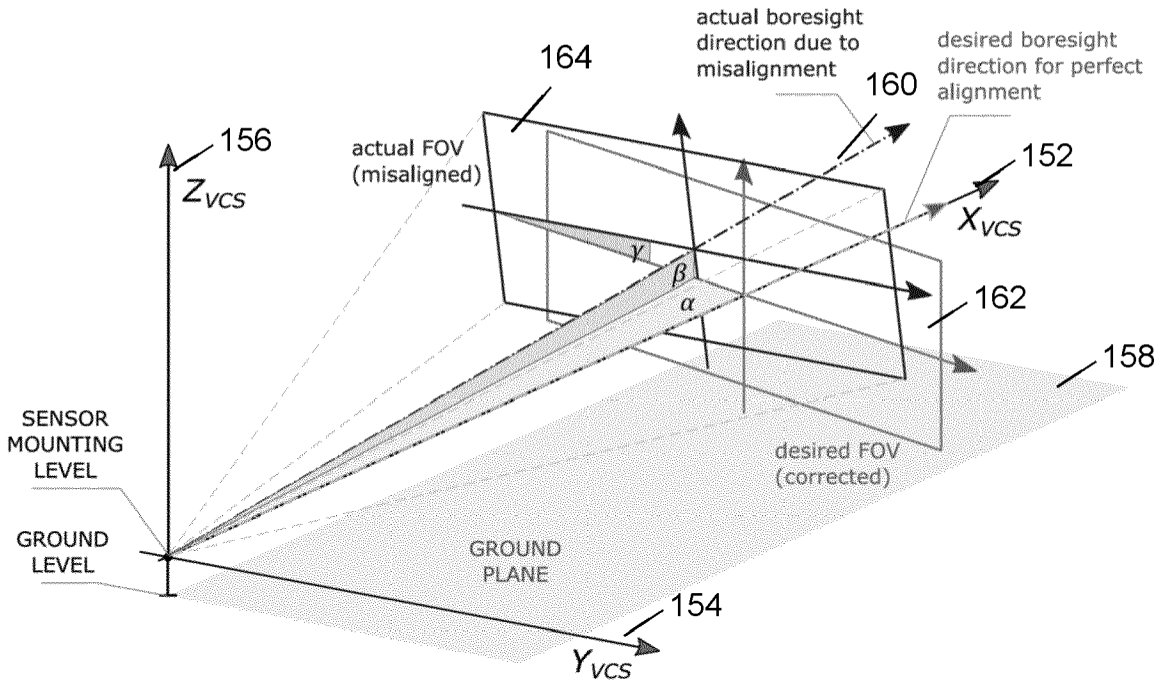
actual boresight
direction due to
misalignment
164
160
desired boresight
direction for perfect
alignment
156
Z_{VCS}
actual FOV
(misaligned)
152
X_{VCS}
γ
β
α
162
158
SENSOR
MOUNTING
LEVEL
desired FOV
(corrected)
GROUND
LEVEL
GROUND
PLANE
154
Y_{VCS}

Fig. 1B

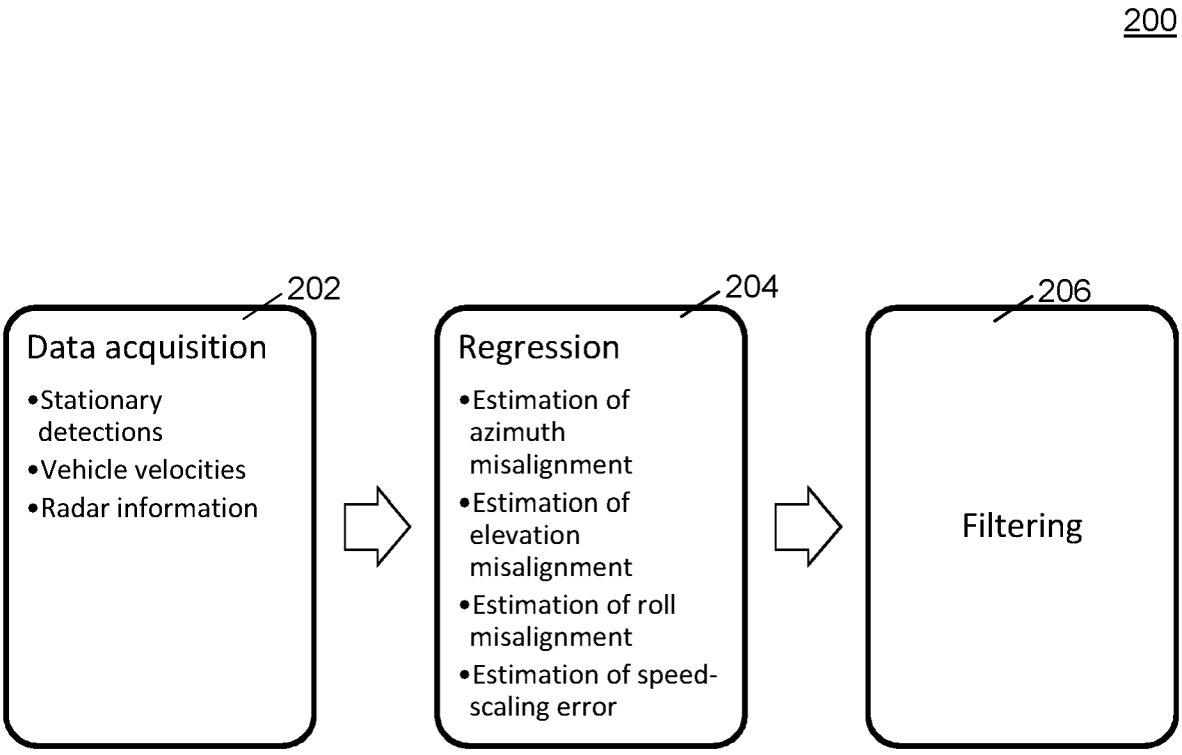
200
202
Data acquisition
•Stationary detections
•Vehicle velocities
•Radar information
204
Regression
•Estimation of azimuth misalignment
•Estimation of elevation misalignment
•Estimation of roll misalignment
•Estimation of speed-scaling error
206
Filtering

Fig. 2

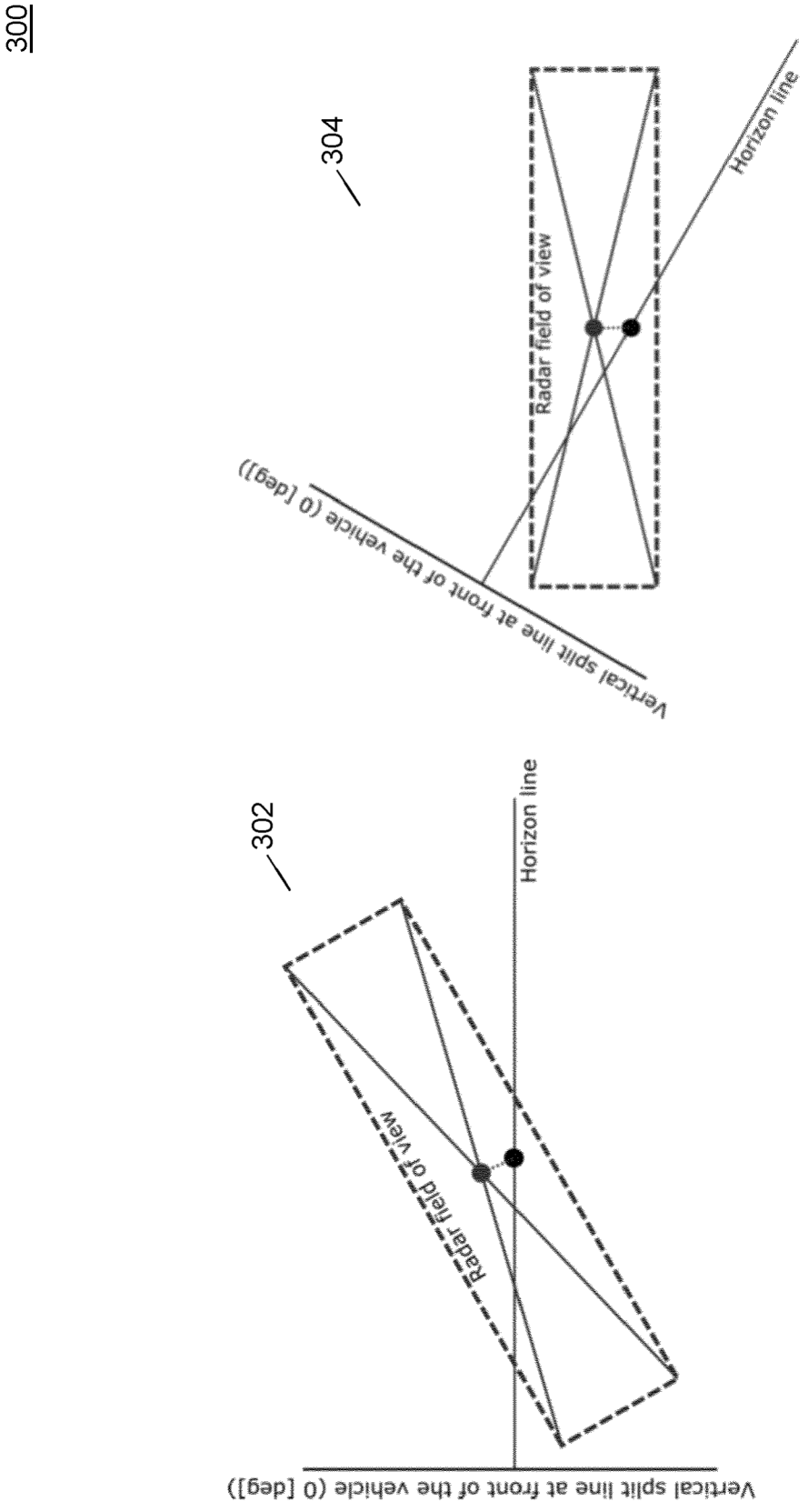
300
304
Horizon line
Radar field of view
Vertical split line at front of the vehicle (0 [deg])
302
Horizon line
Radar field of view
Vertical split line at front of the vehicle (0 [deg])

Fig. 3

400

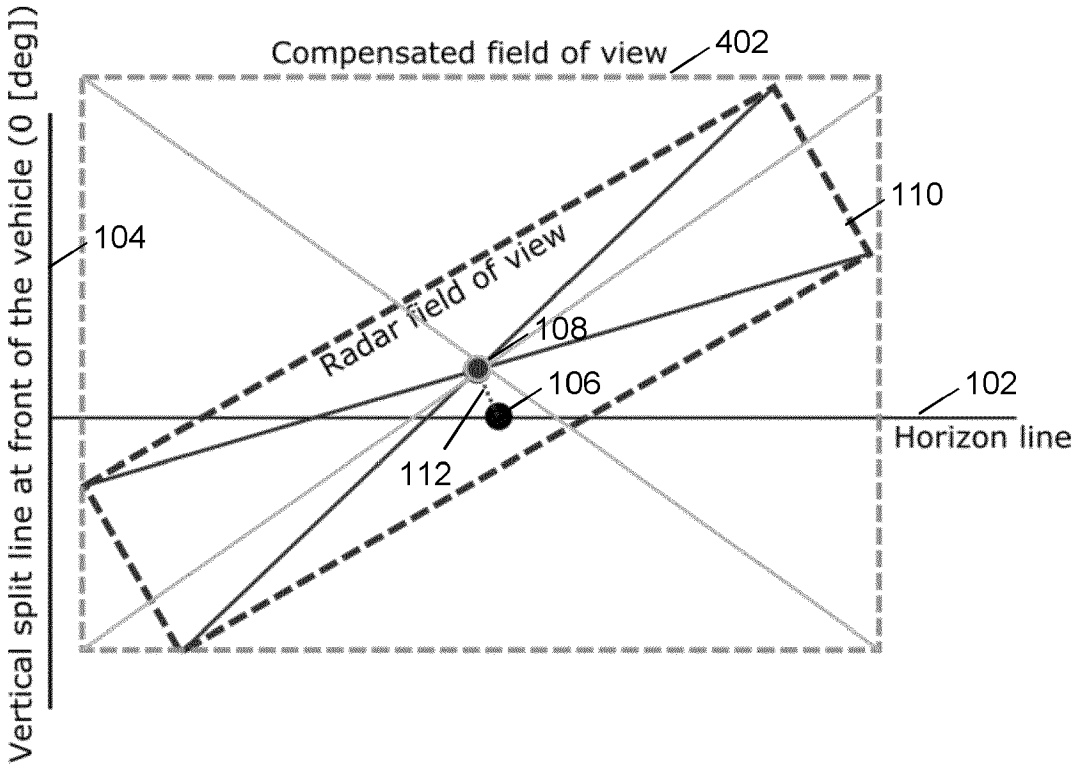
Compensated field of view
402
110
104
Radar field of view
108
106
102
Horizon line
112
Vertical split line at front of the vehicle (0 [deg])

Fig. 4

500

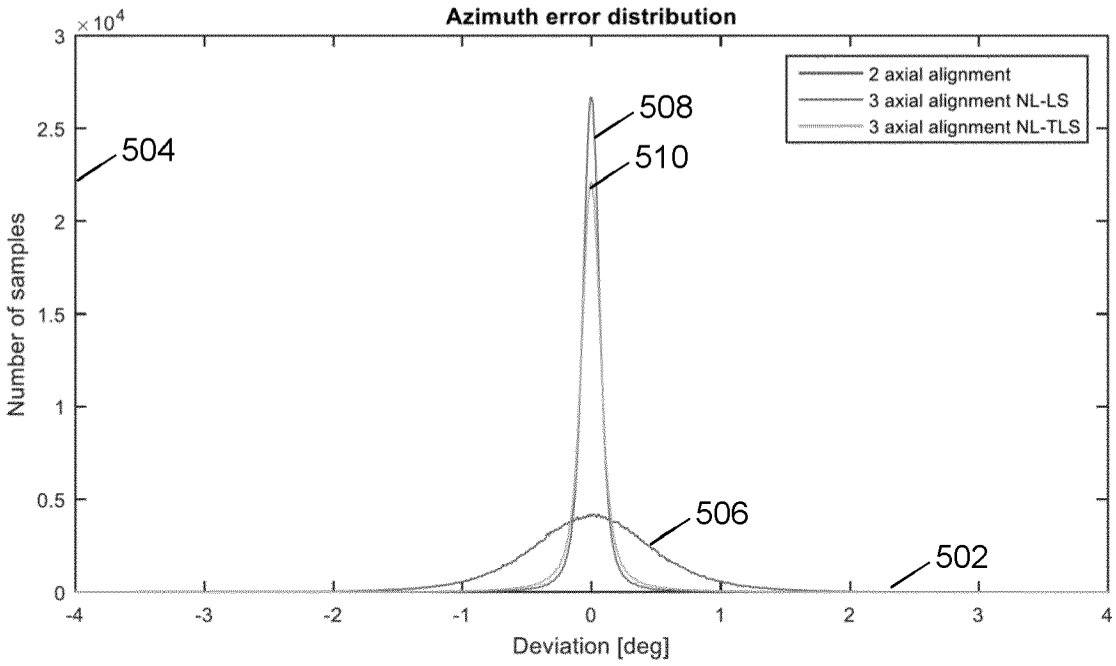
Azimuth error distribution
×10^4
3
2.5
2
1.5
1
0.5
0
Number of samples
-4
-3
-2
-1
0
1
2
3
4
Deviation [deg]
2 axial alignment
3 axial alignment NL-LS
3 axial alignment NL-TLS
504
508
510
506
502

Fig. 5

600

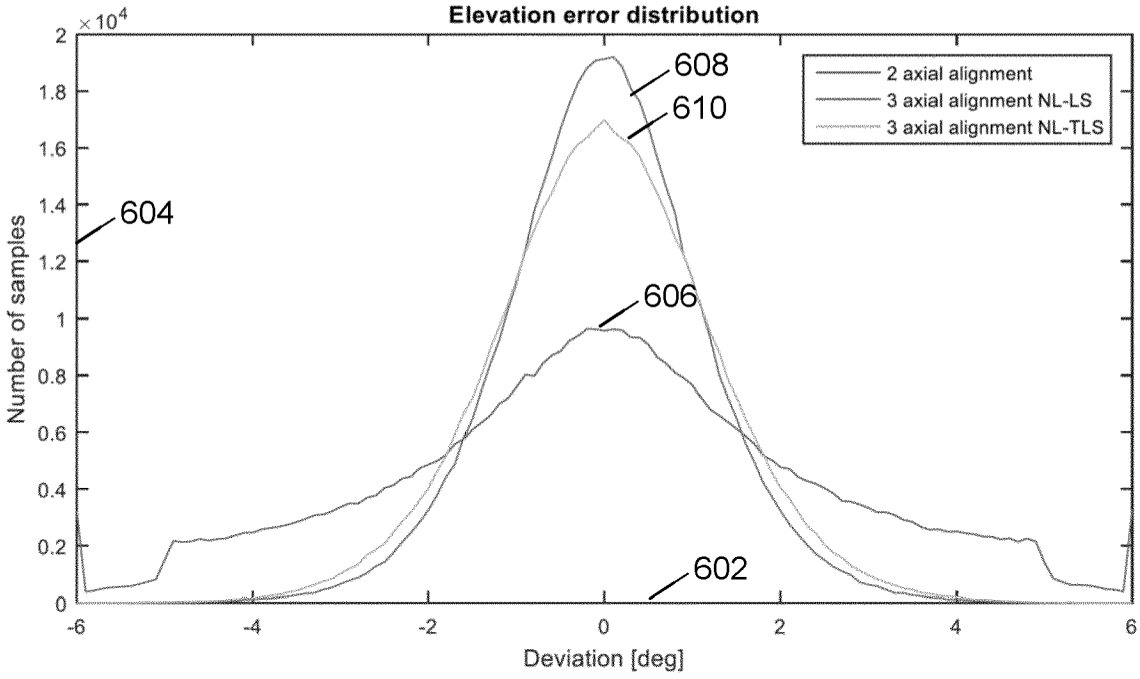
Elevation error distribution
×10^4
Number of samples
Deviation [deg]
2 axial alignment
3 axial alignment NL-LS
3 axial alignment NL-TLS
604
608
610
606
602

Fig. 6

700

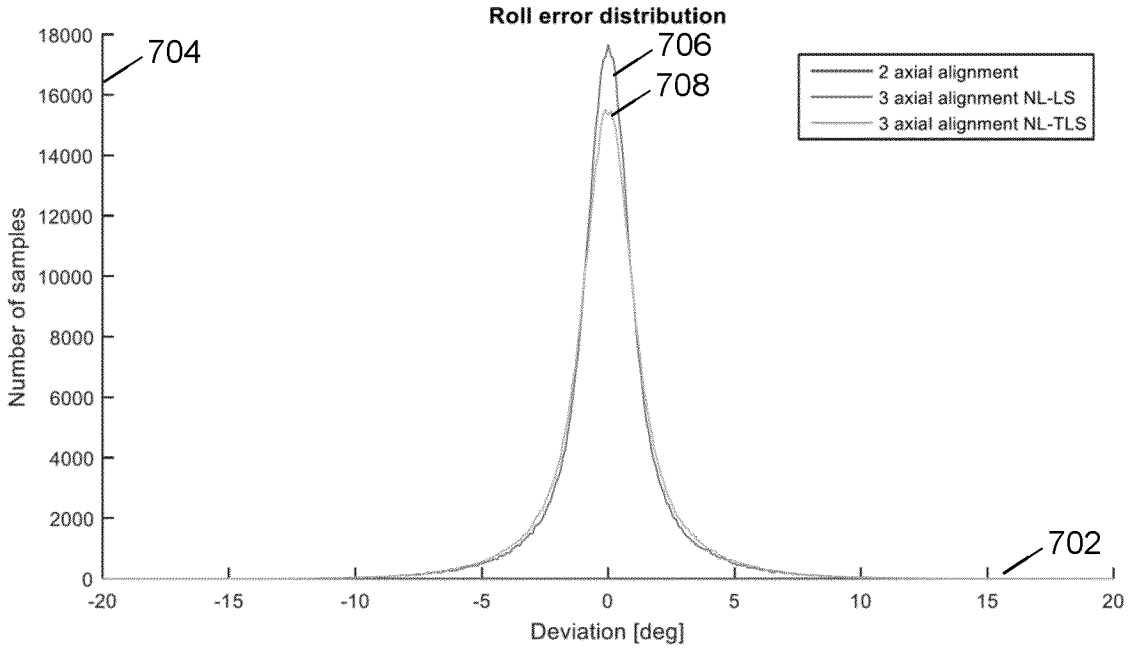

Figure 7 Instantenious roll alignment error distribution (500 000 samples)

Fig. 7

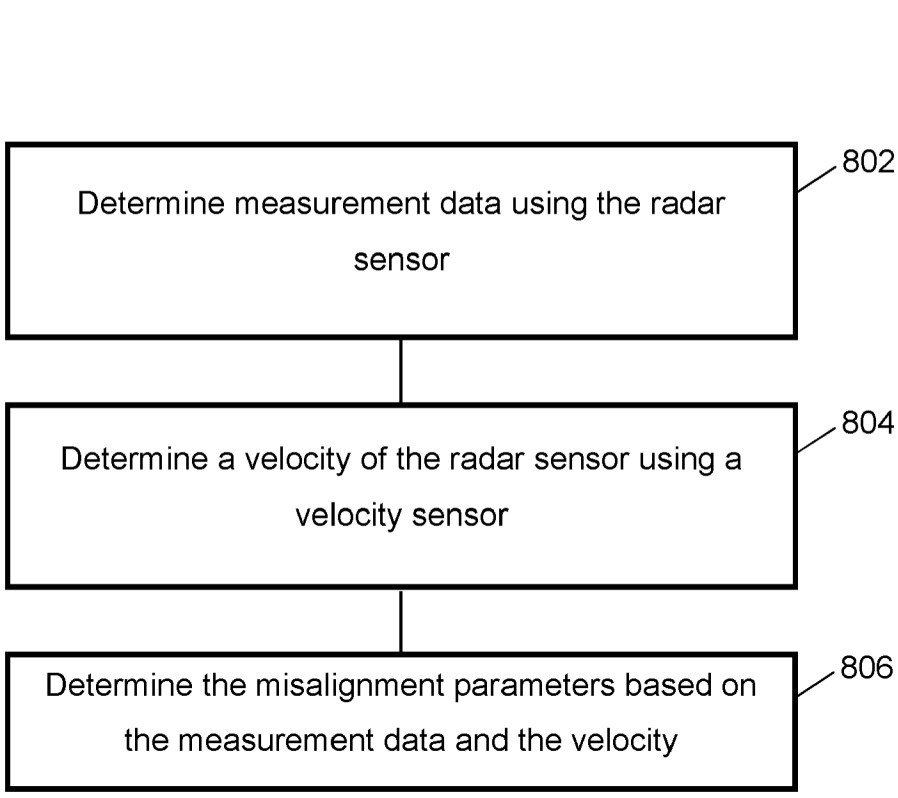
800
Determine measurement data using the radar sensor
802
Determine a velocity of the radar sensor using a velocity sensor
804
Determine the misalignment parameters based on the measurement data and the velocity
806

Fig. 8

900

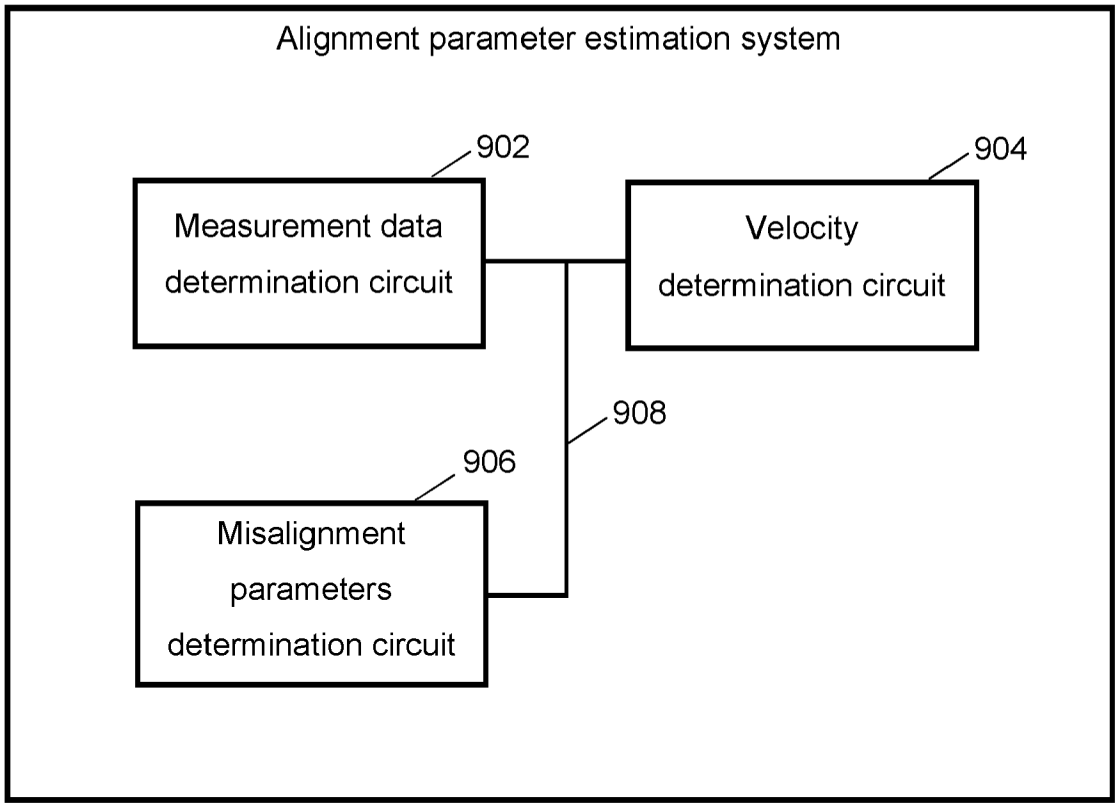
Alignment parameter estimation system
902
Measurement data determination circuit
904
Velocity determination circuit
908
906
Misalignment parameters determination circuit

Fig. 9

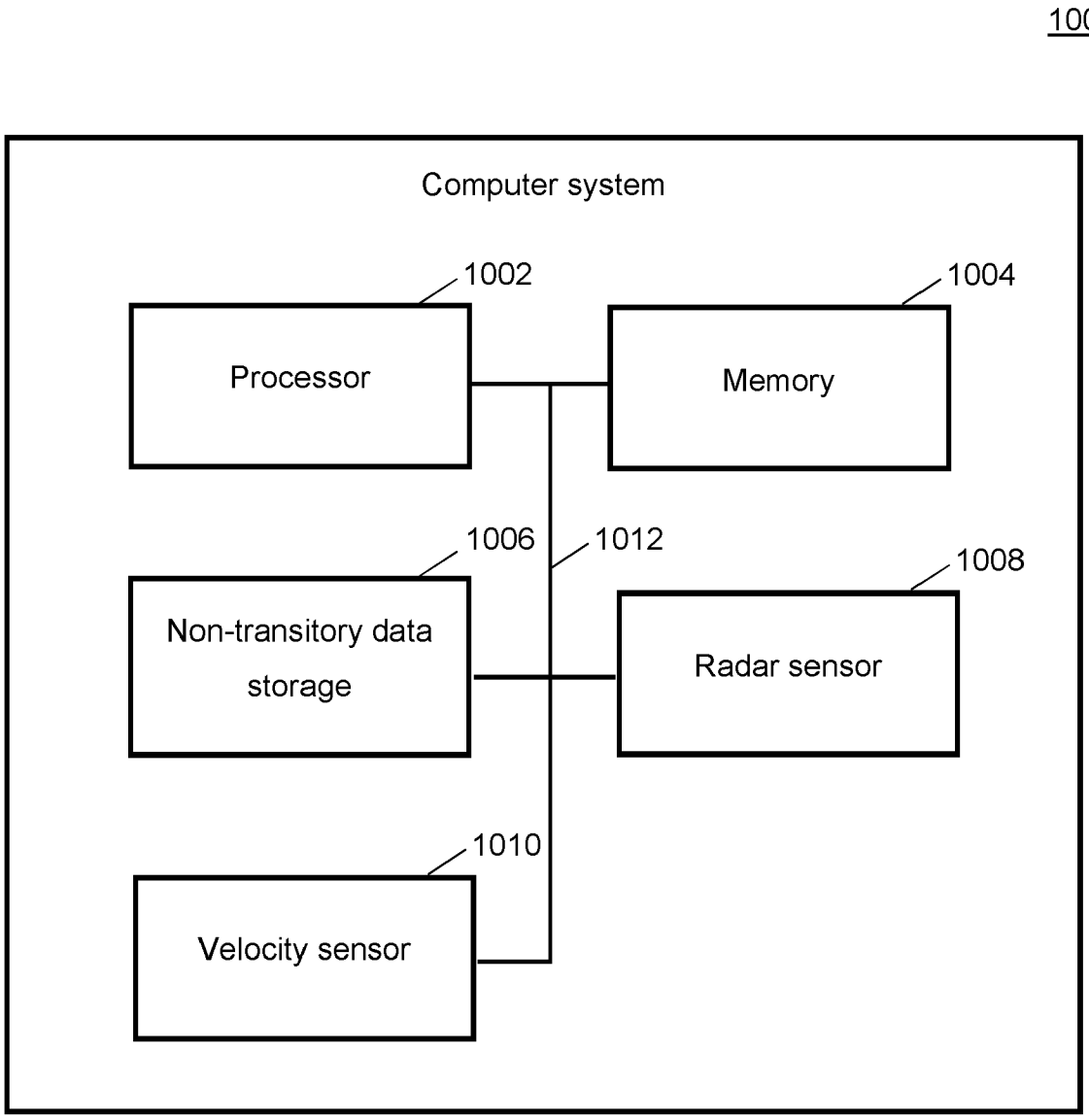
1000
Computer system
1002
Processor
1004
Memory
1006
Non-transitory data storage
1012
1008
Radar sensor
1010
Velocity sensor

Fig. 10

Europäisches Patentamt
European Patent Office
Office européen des brevets

EUROPEAN SEARCH REPORT

Application Number
EP 20 17 2809

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
X	EP 3 279 683 A1 (DELPHI TECH INC [US]) 7 February 2018 (2018-02-07) * the whole document *	1-15	INV. G01S7/40 G01S13/931 G01S13/42
X Y	DE 10 2014 223461 A1 (BOSCH GMBH ROBERT [DE]) 19 May 2016 (2016-05-19) * paragraphs [0007], [0026], [0027], [0041] - [0049]; figures 1,2 *	1,3-15 2	ADD. G01S7/41 G01S13/58
Y	WO 2019/042523 A1 (HELLA GMBH & CO KGAA [DE]) 7 March 2019 (2019-03-07) * paragraphs [0008], [0009], [0013], [0014] *	2	

TECHNICAL FIELDS SEARCHED (IPC)

G01S

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
Munich	8 October 2020	Schmelz, Christian

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
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ANNEX TO THE EUROPEAN SEARCH REPORT ON EUROPEAN PATENT APPLICATION NO. EP 20 17 2809

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08-10-2020

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DE 102014223461 A1	19-05-2016	NONE	
WO 2019042523 A1	07-03-2019	CN 110892281 A	17-03-2020
		EP 3676628 A1	08-07-2020
		US 2020241124 A1	30-07-2020
		WO 2019042523 A1	07-03-2019

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