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A Method of Spatial Calibration for Camera and Radar*

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Abstract **- The technique of multi-sensor fusion has already been used widely in intelligent vehicle environment perception. The spatial calibration of the radar and camera is the basis for road detection with information fusion real-timely. So, a method of spatial calibration of radar and the camera has been proposed to implement the spatial calibration of the two sensors. The non-linear distortion of the camera is considered in the paper. Coordinate transformation between the coordinates relevant to the radar and camera is introduced as the constraints. After transforming the feature between the related coordinates of image and the relative coordinates of radar, the calibration parameters are determined with the least square error function. Experiment results indicate that this method is simple and easy to realize, which has the high accuracy that satisfy requirement of the system.**

Index Terms - camera; laser radar; multi-sensor data fusion, spatial calibration

I. INTRODUCTION

In recent years, environment perception based on computer vision has become a hot research area. However, due to the limitations of machine vision, there are often error or miss detections during the road detection. These problems can be solved with information fusion of radar data and CCD image. To do that, spatial calibration of two sensors which has great influence on the accuracy of information fusion is the basis of realizing information fusion. At present, many scholars at home and abroad proposed a variety of calibration methods for radar and camera [1 ~ 5] which are widely used. Most of algorithms proposed require solving the camera's internal parameters and external parameters at the same time, which caused more calibration parameters to obtain.

In the view of previous studies, a method of spatial calibration for camera and radar is proposed in the paper. In order to improve the algorithm's accuracy and practicality, algorithm takes into account the problem of camera distortion, and implements the non-linear image correction with the distortion coefficients obtained through camera calibration. Coordinate transformation between radar and camera is introduced as the constraint. The calibration parameters of transformation solve with the least square error function. The experiment results proved that the algorithm is simple and easy to implement. And it also has certain anti-interference ability.

II. SENSORS MODEL

In the paper, the basic pinhole model [6] considering distortion has been used. The camera optical center is considered as the origin of camera coordinate, and the z axis is the direction of the camera optical axis. The point $p(x_c, y_c, z_c)$ is in the camera coordinate, and $p_u(u,v)$ is in the image coordinate without distortion. The relationship between them can be described as equation (1). However, because of the distortion caused by perspective projection and other factors, the image coordinate $p_u(u,v)$ is $p_d(x,y)$ actually. The relationship between them can be expressed as equation (2).

$$\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \frac{1}{z_c} \cdot \begin{bmatrix} \alpha & 0 & u_0 \\ 0 & \beta & v_0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} x_c \\ y_c \\ z_c \end{bmatrix} \tag{1}$$

$$\begin{cases} x = u + k_1 \cdot u \cdot r^2 + p_1 \cdot (3 \cdot u^2 + v^2) + 2 \cdot p_2^2 \cdot u \cdot v + s_1 \cdot r^2 \\ y = v + k_2 \cdot v \cdot r^2 + p_2 \cdot (3 \cdot u^2 + v^2) + 2 \cdot p_1^2 \cdot u \cdot v + s_2 \cdot r^2 \\ r^2 = u^2 + v^2 \end{cases} \tag{2}$$

Where the pixel centre of the image coordinate is noted as (u_0, v_0). α, β are defined as $\alpha = f/dx$ and $\beta = f/dy$, f is the focal length of the camera, dx 、 dy represent the distance between two pixels in direction of x and y respectively;. The nonlinear distortion parameters vector is marked as $(k_1, k_2, p_1, p_2, s_1, s_2)$.

For laser radar detection, the raw radar data are expressed in polar coordinate. In the radar scanning plane defined in Fig. 1, the transformation between the polar coordinate and the Cartesian coordinate can be presented as equation (3). Where ρ represents the radar distance data, and θ is the scanning angle of radar.

$$\begin{cases} x_l = \rho \cdot \cos\theta \\ y_l = \rho \cdot \sin\theta \\ z_l = 0 \end{cases} \tag{3}$$

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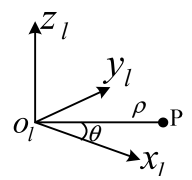

Fig.1 The laser radar scanning plane

III. PARAMETERS SOLUTING

Generally speaking, it can not implement with the method of searching matching for both radar and camera calibration, because it can not find the relevant points in the CCD image since the radar data is invisible and the vertical field angle is small.

But, it is well known that each point of radar data has the fixed angle relative to the laser radar during the radar scanning process. So, for each the point obtained by laser radar, it is can get the only coordinate in the 3-D world coordinate which is according with radar point. And the task of camera is to complete the transformation from the 3-D world coordinate to the 2-D image coordinate. Although it loses the distance information during the transformation, it is true that there is only one pixel to corresponding with a given point in the 3-D world coordinate. Therefore, for any 3-D point, there is only one pixel corresponding point in the image coordinate, and the only one point corresponding in the radar data.

A. *Establishing Sensors Coordinates*

Considering the generality, the installation positions of radar and camera as well as the relative coordinates of them are shown in Fig.2.

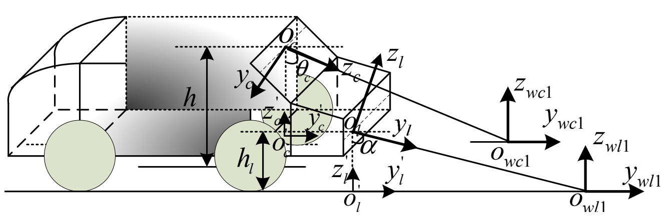

Fig. 2 Installation position of CCD and radar

In Fig.2, the radar coordinate $o_l x_l y_l z_l$ is defined as the following steps: the origin of coordinate denoted as o_l is the position that radar installed in vehicle; y_l axis points to the direction of the front of the radar which is also the vehicle direction when the scanning angle is ninety; and x_l is vertical to paper and straight out of the paper. Meanwhile the camera coordinate $o_c x_c y_c z_c$ can be described as the following: the camera's optical centre is considered as the origin of coordinate denoted as o_c; the axis z_c follows the direction of camera optical axis; and x_c is vertical to paper and straight out of paper. The projection of o_l and o_c are marked as $o_c^{'}$ and $o_l^{'}$. The coordinates of $o_c^{'} x_c^{'} y_c^{'} z_c^{'}$ and $o_l^{'} x_l^{'} y_l^{'} z_l^{'}$ is the reference coordinates of CCD and radar. The coordinate $o_{wc} x_{wc} y_{wc} z_{wc}$ is word coordinate of the camera. And the coordinate $o_{wl} x_{wl} y_{wl} z_{wl}$ is about the word coordinate of the radar. The installation pitch angle of cameras and radar are marked as θ_c and α_l respectively.

The orthonormal rotation matrix and translation matrix between the coordinates in Fig. 2 are shown in Fig. 3. In Fig. 3, the rotation matrixes and translation matrixes from radar coordinate and camera coordinate to there reference coordinates are denoted as R_c, t_c and R_l, t_l respectively. The rotation matrix between camera coordinate and the image coordinate is A. The transformation matrixes between the radar world reference coordinate $o_{cw} x_{cw} y_{cw} z_{cw}$ and the camera' $o_{lw} x_{lw} y_{lw} z_{lw}$ are R_{lc} and t_{lc} correspondingly. The translation matrix between $o_c x_c y_c z_c$ and $o_c^{'} x_c^{'} y_c^{'} z_c^{'}$ is $t_l^{'}$. And $t_c^{'}$ translation matrix is between $o_l^{'} x_l^{'} y_l^{'} z_l^{'}$ and $o_l x_l y_l z_l$.

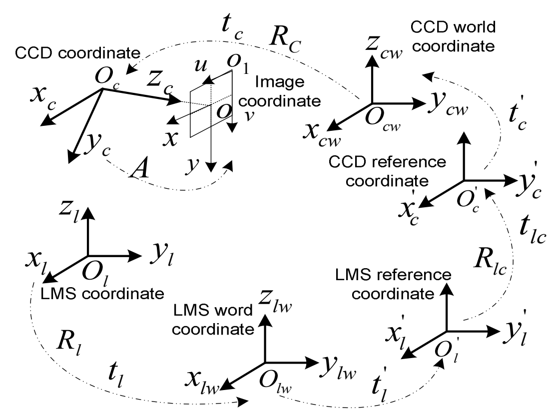

Fig.3 Transformation between coordinates

B. *Equations for Parameters Solution*

According to Fig. 2, supposing that the road is flat, the radar's orthonormal rotation matrix R_l and translation matrix t_l can be got according to right hand rule. The relation in the plane of $z_{wl} = 0$ in world coordinates between radar world coordinate and the radar coordinate can be described as equation (4). As the same for CCD, the transform from the coordinate $o_{wc} x_{wc} y_{wc} z_{wc}$ to the image coordinate $o_c x_c y_c z_c$ can be represented as expression (5) in plane of $z_{wc} = 0$. Where, the pitch angle of camera is denoted as θ_c, installation height of camera is h; h_l is the installation height of radar; the pitch angle of radar is marked as α_l and scanning angle of radar is noted as θ; and the radar distance data is noted as ρ.

$$\begin{bmatrix} x_{wl} \\ y_{wl} \\ z_{wl} \end{bmatrix} = R_l \begin{bmatrix} x_l \\ y_l \\ z_l \end{bmatrix} + t_l$$
$$\begin{cases} x_{wl} = \rho \cdot \cos\theta \\ y_{wl} = \dfrac{\rho \cdot \sin\theta \cdot \cos\alpha_l - h_l}{\sin\alpha_l \cdot \cos\alpha_l} \end{cases} \tag{4}$$

$$\begin{bmatrix} x_c \\ y_c \\ z_c \end{bmatrix} = R_c \begin{bmatrix} x_{wc} \\ y_{wc} \\ z_{wc} \end{bmatrix} + t_c$$
$$\begin{cases} x_{wc} = \dfrac{(u-u_0)\cdot h \cdot \beta}{\alpha \cdot [(v-v_0)\cdot \sin\theta_c + \beta \cdot \cos\theta_c]} \\ y_{wc} = \dfrac{\beta \cdot h \cdot \sin\theta_c - h\cdot(v-v_0)\cdot\cos\theta_c}{(v-v_0)\cdot\sin\theta_c + \beta\cdot\cos\theta_c} \end{cases} \tag{5}$$

The relation between $o_c^{'}x_c^{'}y_c^{'}z_c^{'}$ and $o_l^{'}x_l^{'}y_l^{'}z_l^{'}$ is showing as Fig. 4 in detail. The offsets between the two horizontal and vertical coordinate axes are tx and ty which can be measured when installing the sensors. The distance between $x_c^{'}$ and $x_l^{'}$ is tx . And ty is the distance between $y_c^{'}$ and $y_l^{'}$ .The φ expresses the angle between $x_c^{'}$ and $x_l^{'}$.

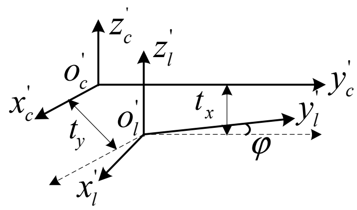

Fig.4 Coordinate relationship between radar and camera

According to the coordinate relationship shown in Fig. 4, we can obtain the relation between coordinate $o_l^{'}x_l^{'}y_l^{'}z_l^{'}$ and coordinate $o_c^{'}x_c^{'}y_c^{'}z_c^{'}$ in plane $z=0$ which is described in equation (6). Where $(x_c^{'}, y_c^{'}, z_c^{'})$ represents the point in coordinate $o_c^{'}x_c^{'}y_c^{'}z_c^{'}$; and $(x_l^{'}, y_l^{'}, z_l^{'})$ is the point in coordinate $o_l^{'}x_l^{'}y_l^{'}z_l^{'}$.

$$\begin{cases} x_l^{'} = \cos\varphi \cdot x_c^{'} + \sin\varphi \cdot y_c^{'} - tx\cdot\cos\varphi - ty\cdot\sin\varphi \\ y_l^{'} = \cos\varphi \cdot y_c^{'} - \sin\varphi \cdot x_c^{'} + tx\cdot\sin\varphi - ty\cdot\cos\varphi \end{cases} \tag{6}$$

C. Parameters solution

It is well known that distances between camera and preceding target shown in Fig.5 can be implemented with the equation (7). In Fig. 5, α is expressed as $\alpha = \theta_c - B/2$; θ_c is the pitch angle of CCD; the vertical field angle of CCD is denoted as B , d_2 is the distance from image near insight to camera, d_1 represents the distance between the CCD near sight and host vehicle.

$$\begin{aligned} & d_c = d_1 + d_2 \\ & d_1 = h\cdot\tan(\theta_c - B/2) \\ & d_2 = ((y_1-y_2)^2 + (x_1-x_2)^2)^{0.5} \end{aligned} \tag{7}$$

Where, (x_1 , y_1) and (x_2 , y_2) are obtained using (5) from the middle coordinates (u_1 , v_1) of target and the image middle coordinate (u_2 , v_2).

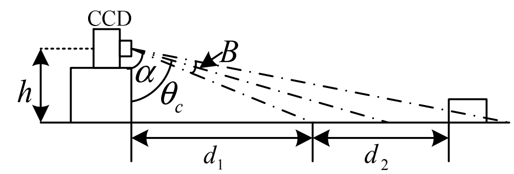

Fig.5 Schematic diagram of measuring distance

The process for getting d_2 can be presented as following steps:

1) Get the image with the CCD.

2) Recognize the target and note it with square.

3) Obtain the middle coordinate (u_1 , v_1) and (u_2 , v_2) of bottom line for square's and the image's.

4) Transform image coordinate marked as (u_1 , v_1) and (v_2 , u_2) to CCD world coordinate noted as (x_1 , y_1) and (x_2 , y_2) with (5). And then the distance d_2 can be got with $d_2 = ((y_1-y_2)^2 + (x_1-x_2)^2)^{0.5}$

In order to realize the calibration of CCD and radar, given a certain change steps for the parameters of θ_c , α_l and φ , the calibration parameters can be obtained by the least square error function shown as definition (8). It is the very value we need to get, when the equation has the least error under a certain value of θ_c , α_l or φ .

$$\min_{R,T} \left\| d - \hat{d}(R,T,p) \right\|^2 \tag{8}$$

Where, d represents the known distance in the word coordinate, $\hat{d}(R,T,p)$ is about the distance obtained with data processing and coordinate transformation. For parameter θ_c ; it represents the distance obtained with image process. For α_l , it means the distance measured with radar. And to φ , it notes the distance got with the data in radar coordinate which is transformed from image coordinate.

IV. EXPERIMENTAL RESULTS

It is mainly to resolve the space calibration between the two sensors in the paper. Firstly, before experiment, the camera is calibrated using the camera calibration method based on the invariant cross-ratio [7] to get the internal parameters. The relative installation position of camera and radar is shown in Fig. 6. In the paper, experiment platform is composed with laser radar-LMS291 and the camera made by fonhoo. Parameters of laser radar set during experiment are with scanning range of 0° ~ 180° and scanning precision of 0.5°.

Fig.6 Sensors using in experiment

In order to verify the effectiveness of the algorithm which has been realized with Matlab, a number of experiments have been carried out in the lab. Parameters of calibration obtained are shown in Table 1. The discontinuous points noted with red ‘ * ’ in Fig.7 are the radar raw data. Fig. 8 shows the experimental results which is about the image with the laser radar data projected to the CCD image under the parameters in Table 2 obtained with the method in the paper. From the experimental results in Fig. 8, we can see that the data in left of the image is more than the right side due to the installation of radar, and not all the laser radar data have been transformed into the image that is because the field angle of CCD is only about 40°. But from Fig. 8, it can get good results of matching of the still target.

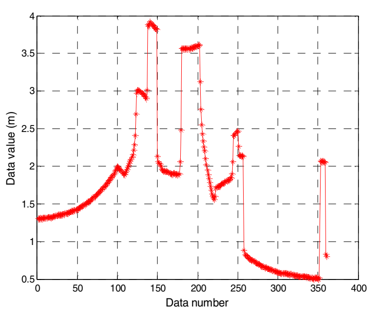

Fig.7 Data got with laser radar

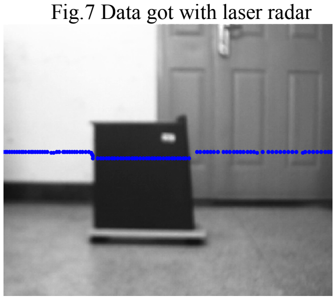

Fig.8 Experimental results from radar to CCD

TABLE 1

REGISTRATION RESULTS OF RADAR AND CAMERA

θ_c	α_l	φ
θ_c =1.5114rad	α_l =1.4854rad	φ =0.0279rad

Experiments also have been done to indicate the accuracy of transformation. When doing the experiments, 12 locations are selected within 50 meters in front of the sensors. Each time one target whose coordinate is known is located. The calibration accuracy of the method is evaluated according to the error between original feature points and the points transformed. The experimental results and error analysis got under the parameters in Table 1 are showing in Fig. 9 and Fig. 10. From the figure of y axis error analysis, we can see that the value of error is increasing with distance growing. That is because in the image the father pixies represent greater distance than the nearer ones. So when the father pixies are transformed into laser coordinate, the errors are greater.

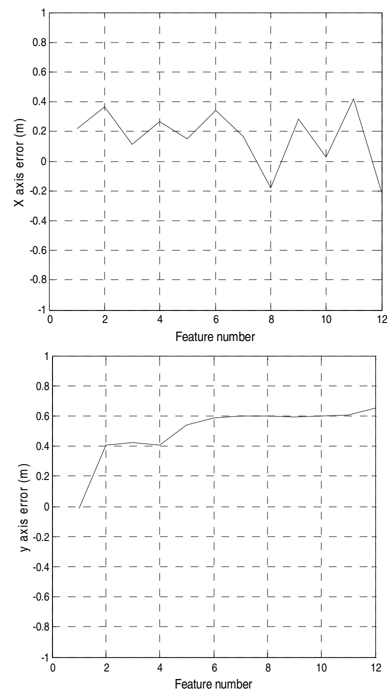

Fig.9 Experimental results of errors in both axes

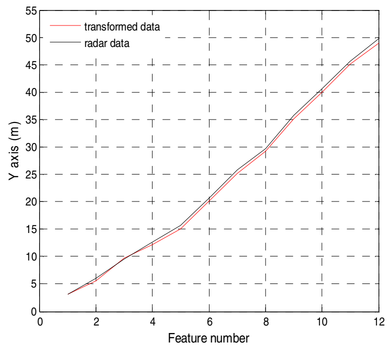

Fig.10 Experimental results for both axes

From the experimental results above, we can see that the algorithm can match the information from the two sensors well. And the calibration accuracy can meet the requirements of practical application for intelligent vehicle.

V. CONCLUSION

In order to realize the spatial calibration for radar and CCD to implement intelligent vehicle environment perception with multi-sensor data fusion, a method of spatial calibration for radar and camera is proposed in the paper. This method is completed with the constraint of coordinate transformation and the distance measured with single camera. The calibration parameters of transformation solve though the optimization algorithm. The experiments indicate that the algorithm is simple, fast, and easy to implement with high precision. After calibration using the method, the information from the two sensors can be matched well together. It is beneficial to the next step of road detection based on information fusion.

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