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On Automatic and Dynamic Camera Calibration based on Traffic Visual Surveillance

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Abstract— **This paper presents a novel automatic and dynamic camera calibration algorithm based on traffic visual surveillance. The algorithm can automatically calibrate the intrinsic and extrinsic parameters of camera, and offer enough guarantee to extract traffic real-time parameters. This paper firstly indicates the significance of applying automatic and dynamic calibration algorithm to intelligent transportation system, then establishes a mathematical model of calibration parameters between camera image and actual road. The algorithm is established from three view points, which are description, flow chart and algorithm description. Afterward this paper describes the experimental method and result based on this novel algorithm. Finally this paper indicates wide application foreground of this algorithm in intelligent transportation system.**

I. INTRODUCTION

Camera calibration is the method of determining the internal geometry and optical characteristics (intrinsic parameters) and the three-dimensional position and orientation of a camera relative to a certain earth coordinate system (extrinsic parameters) for the purpose of inferring the three-dimensional information from computer image coordinate or deducing computer image coordinate from the three-dimensional information[1]. In the problems of many practical application, camera calibration is a basic and important process in computer vision. Such applications can be widely found in robotic and automation, manufacture and measure, visual surveillance and security and so on[2].

In recent two decades, camera calibration has been researched and developed in many universities and scientific institutes. This research has mainly gone through three stages: (a). Traditional camera calibration, makes use of the known scene information and commonly adopts a kind of accurate template similar to calibration block. This method are applicable to all camera models and the accuracy of calibration is very high. However, the process of calibration is very complicated, and a few of structure information must be provided. So this accurate template can not widely be used in many practical applications; (b). Active vision calibration, mainly uses some movement information in camera video image. This method provides the linear solution and high robustness, but not apply to the situation of camera movement or uncontrolled camera; (c). Self calibration method, the character of this calibration only depends on corresponding mutual relation among the analytical images. This method has strong flexibility and the wider application foreground, but non-linear computing and high robustness need improvement further[3].

The traffic video surveillance system not only detects qualitative information of traffic real-time status, such as the flow rates and the vehicle average speeds, but also detects quantitative information, such as the traffic jam degrees and the traffic accidents. The traffic quantitative information from image depends on the accuracy of camera parameters, that is to say, the best of calibration's ability. In practical application, the position and orientation of camera is invariable relative to road, but because of the influence of object movement, thermal effects, environment variation, or other unpredictable factors, the user must reorient or refocus camera parameters by extracting the meaningful three-dimensional information from the new image sequences[2], [4] in order to ensure correctness of the detected traffic parameters.

In the past work, camera calibration research almost uses scene information and camera movement. The camera calibration applicable to traffic visual surveillance utilizes lane markings, vehicle outlines, traffic flow and other objects on the road, the character of which are parallel or perpendicular, to accomplish the calibration system by manual approach[5], [6], [7], [8], [9]. But this manual approach is impracticable, not only consumes plenty of money, time and resources, but also reduces the correctness of the detected traffic parameters. Traffic camera calibration must adopt automatically dynamic calibration techniques.

When implementing dynamic camera calibration for traffic visual surveillance, the following hypothesis are fundamental: (a). The lane markings must be parallel one another, which can compute the coordinate of the vanishing points of these parallel lane markings in the images; (b). The lane markings requires clear and not illegible, otherwise, the algorithm just based on vision can not detect the lane markings in the images of traffic scenes.

Based on the above hypothesis, in the second stage the research of camera calibration establishes a mathematical model of camera parameter based on traffic visual surveillance, which deduces the intrinsic and extrinsic camera

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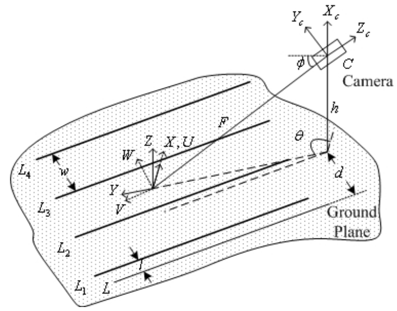

Fig. 1. Single camera and road model figure

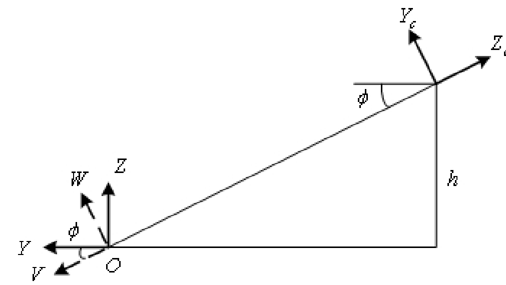

Fig. 2. The plane figure constituted by the lens's main axis and the perpendicular line from camera to ground plane

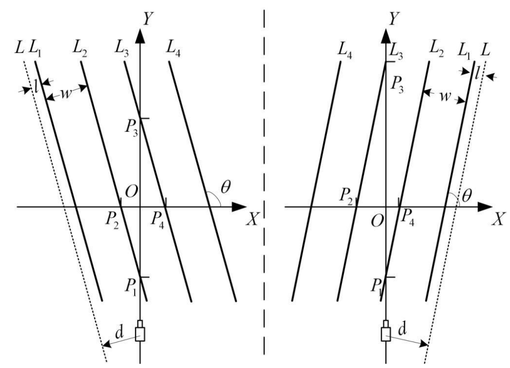

Fig. 3. The road geometry from a bird's eye view with relevant X and Y axis intercepts

parameters from the meaningful image information through the pinhole camera theory and the relation equation of some inherent parameters. In the third stage, this paper advances a novel automatical algorithm to implement dynamic camera calibration. According to this algorithm the next two stages are experimental method and results of estimating camera parameters and computing traffic parameters. Finally the conclusion summarizes application foreground and significance of dynamic camera calibration techniques.

II. Model and Calibration

In order to easily realize this algorithm and applies it widely, this part presents the intrinsic and extrinsic camera parameters expressions convenient for measuring and computing through extracting the character of camera calibration model and traffic visual scene. This camera calibration model mainly describes the interrelations between the camera coordinate system and the earth coordinate system through the physical parameters of pinhole camera optics, including focal length, optical center, pixel size, and the position and the orientation of the camera relative to the earth coordinate system. The characters of traffic visual scene include lane markings parallelism, perpendicularity between no-passing line markings and lane, control information of the traffic light and so on.

In order to deduce and compute interrelation between camera and road model, we firstly extract camera and road information from traffic visual scene. Fig.1 shows a sketch of three lanes and a single camera[10]. L_1, L_2, L_3 and L_4 are four parallel lane markings, L is the one of two road edge lines; w is the lane width between the parallel lanes, l is width between lane line L_1 and road edge line L, d is the perpendicular distance from the edge of the road, h is perpendicular distance from the camera to the ground plane.

The three-dimensional Fig.1 can be decomposed into two planar figures, Fig.2 and Fig.3. Fig.2 consists of optical center axis and the perpendicular line from the camera to ground plane, at the same times builds camera coordinate system (X_c, Y_c, Z_c) (the X_c axis is perpendicular to paper facing inside), earth coordinate system (X, Y, Z) (X is the same direction to X_c), camera-shift coordinate system (U, V, W), which can be obtained by rotating an angle ϕ around the X axis (the U axis is the same direction to the X axis) of the earth coordinate system. $\phi(\phi \in (0, \pi/2))$ is the tilt angle of the camera. Fig.3 is the road geometry from a bird's eye view with relevant X and Y axis intercepts, and $\theta(\theta \in (0, \pi/2) \cup (\pi/2, \pi))$ is the pan angle with respect to the road[11].

From Fig.2, Fig.3 and projective geometry, the relation[10], [11] between (u, v) and (X, Y, Z) is deduced as follows:

$$u = f \cdot \frac{X}{Y\cos\phi - Z\sin\phi + h\csc\phi} \tag{1a}$$

$$v = f \cdot \frac{Y\sin\phi + Z\cos\phi}{Y\cos\phi - Z\sin\phi + h\csc\phi} \tag{1b}$$

Because the Z coordinate of any point on the ground plane is equal to zero($Z = 0$), the expression (2) is deduced as follows:

$$u = f \cdot \frac{X}{Y\cos\phi + h\csc\phi} \tag{2a}$$

$$v = f \cdot \frac{Y\sin\phi}{Y\cos\phi + h\csc\phi} \tag{2b}$$

From Fig.3 the mutual relation expression of the lane markings as follows:

$$Y = \tan\theta \cdot X + k \tag{3}$$

So,

$$\lim_{Y\to\infty} \frac{X}{Y} = \cot\theta \tag{4}$$

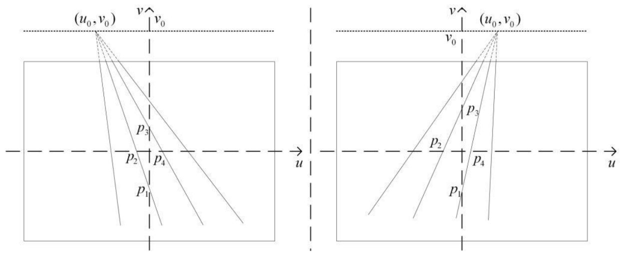

Fig. 4. Outline figure of the lane markings

Consequently the vanishing point coordinate of parallel lane markings in traffic image is deduced on conditions of $Y \to \infty$,

$$u_0 = \lim_{Y\to\infty} f \cdot \frac{X}{Y\cos\phi + h\csc\phi} = f \cdot \cot\theta \cdot \sec\phi \quad (5a)$$

$$v_0 = \lim_{Y\to\infty} f \cdot \frac{Y\sin\phi}{Y\cos\phi + h\csc\phi} = f \cdot \tan\phi \quad (5b)$$

From Fig.3, L_2 and L_3 intersect the X axis and Y axis at $P_1(0,Y_1)$,$P_2(X_2,0)$,$P_3(0,Y_3)$ and $P_4(X_4,0)$. According to expression 2(a) and 2(b), the corresponding coordinates of $P_1 \sim P_4$ in the image plane are expressed as

$$v_1 = f \cdot \frac{Y_1\sin\phi}{Y_1\cos\phi + h\csc\phi} \quad (6a)$$

$$u_2 = f \cdot \frac{X_2}{h\csc\phi} \quad (6b)$$

$$v_3 = f \cdot \frac{Y_3\sin\phi}{Y_3\cos\phi + h\csc\phi} \quad (6c)$$

$$u_4 = f \cdot \frac{X_4}{h\csc\phi} \quad (6d)$$

In addition, there are six relation expressions between Y_1, X_2 and Y_3,X_4 as follows:

$$Y_1 = -X_4 \cdot \tan\theta \qquad \theta \in (0, \pi/2) \quad (7a)$$

$$Y_3 = -X_2 \cdot \tan\theta \qquad \theta \in (0, \pi/2) \quad (7b)$$

$$Y_3 - Y_1 = w \cdot \sec\theta \qquad \theta \in (0, \pi/2) \quad (7c)$$

$$Y_1 = -X_2 \cdot \tan\theta \qquad \theta \in (\pi/2, \pi) \quad (7d)$$

$$Y_3 = -X_4 \cdot \tan\theta \qquad \theta \in (\pi/2, \pi) \quad (7e)$$

$$Y_3 - Y_1 = -w \cdot \sec\theta \qquad \theta \in (\pi/2, \pi) \quad (7f)$$

Combining and deducing these expressions from expressions (5) to (7) as follows:

$$\frac{1}{v_1} + \cot\theta \cdot \csc\phi \cdot \frac{1}{u_4} = \frac{1}{v_0} \qquad \theta \in (0, \pi/2) \quad (8a)$$

$$\frac{1}{v_1} + \cot\theta \cdot \csc\phi \cdot \frac{1}{u_2} = \frac{1}{v_0} \qquad \theta \in (\pi/2, \pi) \quad (8b)$$

$$u_4 - u_2 = \frac{\cos\phi}{\sin\theta} \cdot \frac{w \cdot v_0}{h} \quad (8c)$$

We can detect the coordinates of $p_1(0, v_1)$, $p_2(u_2, 0)$, $p_3(0, v_3)$ and $p_4(u_4, 0)$ from Fig.4 in the traffic scene. v_0, v_1, u_2, v_3 and u_4 can be worked out by some image processing algorithms. h and w are two known variables by measuring the height of the camera and the width of the lanes which are invariable in the special traffic scene. So there are four constraint equations including (5b), 8(a), 8(b) and 8(c); v_0, v_1, u_2, v_3, u_4, h and w are seven known variables, and f, ϕ and θ are unknown variables, but these three unknown variables can be computed according to these four constraint equations, therefore, Y_1, X_2, Y_3 and X_4 can be also computed through four equations that are 6(a$\sim$d).

III. DYNAMIC CALIBRATION ALGORITHM

Because the outside factors affect the camera parameters to result in the inaccuracy of traffic parameter estimation from traffic visual image, this part advances a dynamic calibration algorithm, which solve the above problem. In addition,this algorithm satisfies the automatic and real-time requirement of detecting traffic parameters.

In this part, in order to get the relation between the parallel lines in traffic scene and the vanishing points according to the parallel lines in the traffic images, we refer to the following the relational theorem[12] corresponding to the above description: (a). A group of parallel lines pass through the same infinite far point, that is to say, all those lines passing through the same infinite far point parallel one another; (b). Each group of parallel lines respectively intersects at the different infinite far points; (c). All the infinite far points in the same plane locate the same infinite far straight line.

From the model and calibration of the second part and the above theorem, we can deduce the following conclusions: on the flat or approximately flat road, at least one group of lane markings is parallel, which can intersect into the same vanishing point in the extending part of camera image. If only image processing algorithm obtains Y coordinate of the intersected vanishing point, those intersection coordinates of two parallel lane lines at X and Y axis, the known the height of camera and the width of the lane, we can estimate the intrinsic and extrinsic camera parameters in the traffic scene.

The following process is description of dynamic camera calibration:

1) Obtain the video and image as the calibration samples from the camera fixed on the staff of traffic intersection;
2) Detect the lane markings in the samples by using various image processing algorithms;
3) Compute intersection coordinate of the vanishing points of those parallel lines in the image samples through establishing the image coordinate systems;
4) Estimate the intrinsic and extrinsic camera parameters (f, θ, ϕ) according to the conclusion of the second part;
5) Compare these computed parameters with those using ones in vision system, and confirm whether instead of those using ones or not;
6) Finish this calibration, restart this calibration algorithm to adjust these camera parameters at intervals or at the fixed time.

Fig.5(a) is the process chart of this dynamic algorithm. The dashed frame part is the key of dynamic calibration algorithm, which starts to amend the camera parameters at

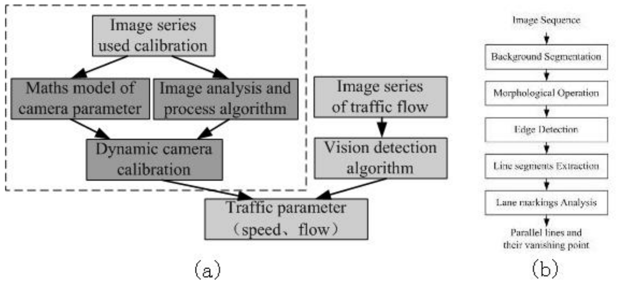

Fig. 5. (a) The process chart of this dynamic algorithm; (b) The process chart of the lane markings detection algorithm

Fig. 6. Image sequence for background extraction

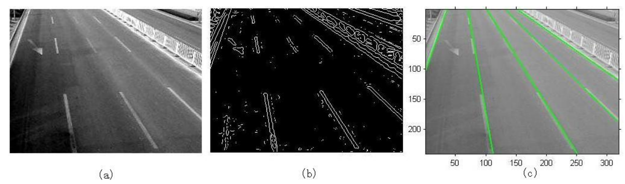

Fig. 7. Some processed traffic images

intervals or at the fixed time. According to the calibrated camera parameters, we can estimate the real-time traffic parameters, including flow rates, average vehicle speeds, traffic jam levels, etc.

In the view of implementation, the following part presents the program algorithm:

$Parameter[\ ]$;//define camera parameters

$DynamicCalibration(Figure[\ ], nParameter[\ ])$; //compute the new camera parameters

{

$Double \quad v0, v1, u2, v3, u4, h, w$; //define the temporary variables

$Figure[\ ] = getFigure()$; //obtain the processed image information

$dealFig(Figure[\ ])$; //detect the lane markings

$compute(v0, v1, u2, v3, u4)$; //compute the intersection coordinate of the parallel line in camera image, four intersections coordinate between the parallel line and X or Y axis.

$getParameter(nParameter[\ ])$; //obtain the camera parameters corresponding to the image sequences

$compare(nParameter[\ ], Parameter[\ ])$; //compare this computed parameters with the using ones, whether or not replace

}

IV. Experimental method

To demonstrate the feasibility of the proposed automatically dynamic calibration algorithm, we firstly provide the image processing algorithm to detect the lane markings and then establish the image coordinate to obtain the requested intersections coordinate, so we can obtain the camera parameters through computing those constraint equations of the second section.

In the first place, an image processing algorithm is proposed automatically to detect the parallel lane markings in the image. The whole algorithm comprises background segmentation, morphological operation, edge extraction, line segments extraction and lane markings analysis. Fig.5(b) shows the process chart of the lane markings detection algorithm.

A. Background Segmentation and Morphological Operation

A novel background extraction for video image sequence[13] is proposed that is applied to vision-based traffic detection. Background is updated by recursion and batch process according to the values of image pixel modeled as a Gaussian model. For urban traffic, the time which background is extracted from the image sequence depended on the state of the current traffic control signals, that is to say, background extraction is processed when the vehicle is in the transit state.

Fig.6 are six continue images from traffic video sequence, and the camera used in the experiment is a Canon S3 digital camera. The image sequences were captured with a resolution of 320×240 pixels. Using Matlab Image Tools these color images are translated to gray images, then adopting the appropriate morphological operation to acquire binary images. In the image process some functions in Matlab are used, such as rgb2gray, imadjust, imtophat, etc. Fig.7(a) shows the result of background extraction, which will be further processed for detecting the lane markings.

B. Edge Detection and Line Extraction

Edge detection plays an special role in image processing and computer vision, and acts as the one important part of bottom-level vision processing. Matlab Image Tools provide a few of operators, such as Robert, Sobel, Prewitt, LoG, Canny and Zero-cross method[14], which have been introduced in many image processing books. Furthermore, the lane markings have two edges, so in the process of edge one edge of which will be eliminated through the length discrimination described by Andrew H.S.Lai[15]. The following step in the process selects one operator, which should be depend on the characteristic of image. For example, edge detection of the traffic image requires to obtain all-direction edge, so

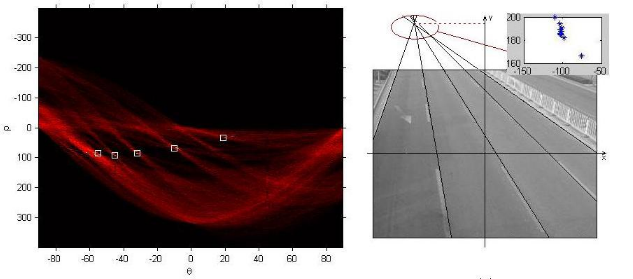

Fig. 8. (a)Hough transform for the Fig.7(b); (b) result of lane detection in traffic image through some image processing algorithms

LoG operator should be used. Fig.7(b) shows the result of edge detection of Fig.7(a) using LoG operator in Matlab.

This paper uses Hough Transform to find lines in an image. The hough function implements the Standard Hough Transform, which uses the polar coordinates representation of a line:

$$\rho = x * \cos\theta + y * \sin\theta$$

The variable ρ is the distance from the origin to the line along a vector perpendicular to the line. θ is the angle between the x-axis and this vector. Fig.8(a) shows Hough Transform figure of the binary image Fig.7(b). In this process, the first step is peak detection, the second one is segment link. Among which the five white small panes denote peaks in Hough Transform, the coordinate of which are corresponding to the lane markings in traffic image. Through segment link processing, we can obtain the link lines of lane markings providing the necessary preparation for camera calibration. Fig.7(c) shows the acquired lane markings in traffic image.

V. Experimental results

According to the above experimental method, Fig.8(b) shows the result of lane detection in traffic image through some image processing algorithms. The image coordinate system was established on the traffic image. The following are the algebraic equations of the detected five lane markings line, the axis scale is one pixel:

$$y = -5.671x - 394.824 \tag{9a}$$

$$y = -1.600x + 024.752 \tag{9b}$$

$$y = -1.000x + 090.434 \tag{9c}$$

$$y = -0.700x + 113.217 \tag{9d}$$

$$y = +2.904x + 483.058 \tag{9e}$$

Through computing these equations, there are ten points of intersection as follows:

$$I_1(-103.065, 189.655) \quad I_2(-103.887, 194.321)$$
$$I_3(-102.201, 184.758) \quad I_4(-102.377, 185.755)$$
$$I_5(-109.470, 199.904) \quad I_6(-098.294, 182.023)$$
$$I_7(-101.755, 187.561) \quad I_8(-075.943, 166.377)$$
$$I_8(-100.673, 190.673) \quad I_{10}(-102.620, 185.051)$$

TABLE I

Experimental data and Error analysis

Ri / Ed	1	2	3
$v_1(pixel)$	483.058	483.058	483.058
$u_2(pixel)$	-166.342	-166.342	-166.342
$v_3(pixel)$	-394.824	24.752	113.217
$u_4(pixel)$	-69.621	15.470	161.739
$f(pixel)$	832	380	240
$\theta(degree)$	96.8^o	103.5^o	108.5^o
$\phi(degree)$	12.6^o	26.1^o	37.8^o

TABLE II

(continued)Experimental data and Error analysis

Ri / Ed	4	5	6
$v_1(pixel)$	-394.824	-394.824	24.752
$u_2(pixel)$	-69.621	-69.621	15.470
$v_3(pixel)$	24.752	113.217	113.217
$u_4(pixel)$	15.470	161.739	161.739
$f(pixel)$	273	202	179
$\theta(degree)$	107.2^o	110.5^o	111.3^o
$\phi(degree)$	34.3^o	42.8^o	46.2^o

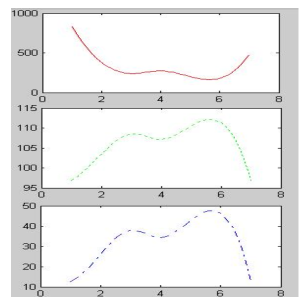

Fig. 9. The spline graph of f, θ and ϕ according to the table I and II

In the right-top of Fig.8(b), it is shown that the coordinate drawing of the above ten points. Using Clustering method in Matlab Tools, such as pdist, linkage and cluster, these ten points can be divided into two classes, which respectively describes the valuable datum, including I_1, I_3, I_4, I_7 and I_{10}, and the error datum. Matrix V_0 is synthesized by five effective points, as follows:

$$V = [I_1^T \quad I_3^T \quad I_4^T \quad I_7^T \quad I_{10}^T]^T$$

V_0 can be worked out by using the mean and std functions in Matlab, the mean function treats the columns of V as vectors and returns a row vector of mean values, and the std function returns a row vector containing the standard deviation of the elements in each column of V, as follows:

$$mean(V) = [-102.404 \qquad 186.556]$$
$$std(V) = [0.486 \qquad 2.046]$$

According to the value of $mean(V)$, the equation $9(c)$ should be eliminated because it is too far for the distance from the $mean(V)$ point to this straight line, four detected lines are left. Then it is necessary for obtaining the camera parameters to select two detected lane markings, actually the four lines all be put into computing for estimation accuracy.

Some coordinates are the required variables when computing the camera parameters according to the second section,which are $v_0 = 186.556$, v_1, u_2, v_3, u_4; besides, $w = 3.35m$ and $h = 6.32m$ are obtained through measuring the width of road and the height of camera.

In table I and II, Ed is the abbreviation of Experiment data and Ri is the abbreviation of Result index. Fig.9 shows the spline graph of f, θ and ϕ from top to bottom respectively, from which the two sides of curve affect the accuracy of the required data, so the two sides must be considered to delete when computing f, θ and ϕ through the graph of these parameters. After analyzing Fig.9, the curve shows the deviation of two sides are very serious, so the Harmonic mean is considered to use only the middle part of the curve. The following is the Harmonic mean of f, θ and ϕ, and the harmmean function calculates the harmonic mean of a sample in Matlab:

$$f = harmmean(f_{curve}) = 217.55$$
$$\theta = harmmean(\theta_{curve}) = 109.3^o$$
$$\phi = harmmean(\phi_{curve}) = 39.5^o$$

The length of two discretional points in traffic image will be worked out after acquiring the camera parameters according to the equations 6(a∼d), sequentially the vehicle speed can also be computed through distance divided by interval, which depends on the rate and numbers of video frame. In addition, this method may be also applied to deal with incidents in traffic road, for example brake trace. At the same time, occupancy ratio can be obtained through the numbers of vehicle passing this segment road in unit time.

For example, the length of v axis in the image when u is equal to zero according to the above equation 2(b) as follows:

$$L = \frac{2vfh}{f^2 \sin^2 \phi - v^2 \cos^2 \phi} \tag{11}$$

thereinto $v = \frac{image\ height}{2}$. In this sample, the image size is 320×240, that is to say, the height of image is equal to 240 pixels. Therefore, the length of L is $33.2m$.

The experimental results of this sample indicate that this algorithm can solve the camera calibration in traffic scenes, and as far as two parameters including the width of lane and the height of camera can be provided, this algorithm can work out these parameters of the camera that are f, θ, ϕ. In addition, it found a favorable foundation furthermore to compute the other traffic parameters combining traffic images.

VI. Conclusion

This paper establishes the road and camera model in more details, and deduces the intrinsic and extrinsic camera parameters from the camera image information, and provides automatically dynamic camera calibration based on traffic visual surveillance. In the view of application, camera will have played an important role in the road visual surveillance among the urban management, and this algorithm provides the better solution for many camera parameters to be adjusted, so this algorithm will greatly accelerate the camera application in intelligent transportation development.

In the future, the automatic algorithm of dynamic camera calibration needs further research. For example, the question that computing camera parameters from the model provided by the second part will be explored. In addition, we will develop video and image processing algorithms in order to extracting camera parameters as precise as possible. On the other hand, the question how to reflect traffic status exactly through quantitative datum will be continue to researched.

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