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A Highway Video Monitoring Method for Precise Positioning Based on Active Spatiotemporal Control

Bin Xie, Jian Wan and Shuyue Li +

China Design Group Co., Ltd., China

Abstract. In response to the challenges faced by traditional passive artificial monitoring modes in unleashing the monitoring capabilities of PTZ (Pan/Tilt/Zoom) cameras, a highway video monitoring method for precise positioning is proposed. This method involves quantitatively matching different preset positions of cameras with milestone numbers, achieving active spatiotemporal control through customized query conditions such as time and milestone numbers. First, research is conducted on camera calibration techniques for comprehensive coverage of segment video monitoring and the matching of camera preset positions with milestone numbers based on imaging principles. The maximum shooting distance of the camera is determined and set, and a direct conversion relationship between camera preset positions and milestone numbers is established. Secondly, a practical method and technological process for implementing a highway video monitoring system for precise positioning are proposed. Finally, a specific application validation is carried out on National Highway 204 Nantong Section. The results indicate that the accuracy of precise positioning queries of the preset position matching model reaches 87%. In terms of monitoring response time, it is more than five times higher in efficiency compared to manual monitoring, making it suitable for large-scale promotion and application in highway network video monitoring.

Keywords: Intelligent transportation, Highway video monitoring, spatiotemporal control, Imaging principles, precise positioning

1. Introduction

In traditional road network video monitoring mode, highway video monitoring inspection system mainly relies on manual patrol. Duty officer gets event info passively via video screen or other means, then manually operates facilities to switch to optimal angle, and records/processes events. But this manual mode requires on-duty personnel to manually operate control head with frequent switching, hard to fully utilize video monitoring coverage of existing high-definition PTZ camera. Existing road network operation monitoring system focuses on camera's fixed preset position, difficult to tap potential of existing video facilities, unable to provide accurate positioning inspection info services for highway road network management and maintenance inspections.

At present, to improve highway video inspection efficiency, there are relevant results of PTZ camera active control and milepost positioning matching at home and abroad. To accurately segment pre-positioned images, the key is to find motion vectors, requiring research on video image sequence motion estimation. The block matching method is simple but has limitations [1] . The optical flow method is mainstream, and there are variations like combining the matching algorithm with the variational optical flow method [2-5] . Meinhardt et al [6] created a pyramid structure. Zhu et al [7] proposed an improved method. Another way is the camera calibration method [8]-[9] .

In addition, at the pre-positioning practical application level, Peng Xiao et al. [10] designed a PTZ control system for substation intelligent inspection robots with good control accuracy and accurate PTZ attitude. ZTE [11] and Fan Zhang et al. [12] feed position info to video terminal via mic for camera to quickly focus on speaker, applicable to most civilian occasions. Youjie Zhang et al. [13] proposed a method based on image analysis for low-cost, high-precision head pre-position control on ordinary medium and heavy heads. Galen Peng et al. [14] proposed a gimbal control strategy idea combining Faster R-CNN and fuzzy PID.

+ Corresponding author. Tel.: 86-17826529991.
E-mail address: 985705308@qq.com.

In summary, existing results mostly based on deep learning detection methods, need enough samples for training, hard to adapt to complex highway traffic env. For existing problems, paper proposes highway accurate positioning video monitoring method for custom active spatiotemporal control query conditions. First, based on camera imaging principle, discretise unstructured continuous video data to match highway spatial ref info for different presets. Second, for different mileage ranges, highways can auto adopt corresponding PTZ rotation and optical zoom for active dynamic video monitoring mode. Finally, via analysis of specific examples, verify model's rationality and validity, further improve highway video monitoring efficiency.

2. Preset Bit Matching Model

2.1. Preset Position Calibration Technology

2.1.1. Preset Bit Model Construction

Each video point basically has two monitoring directions, upstream and downstream, from the initial position of the upstream to the final position of the downstream, in accordance with the requirement that there should be sufficient cross range of roadway monitoring between the images taken by neighboring preset positions, which can be sequentially calibrated as the limit preset position (upstream initial), the intermediate preset position (1, 2, 3, ...) , limit preset position (downstream final), as shown in Figure 1.

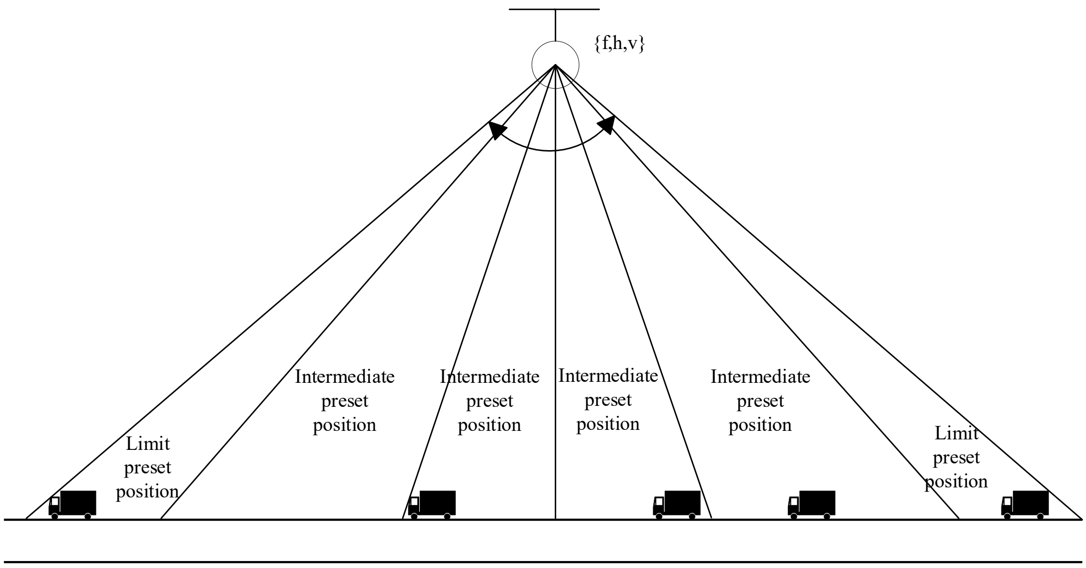


Fig. 1: Preset-position model

2.1.2. Limit Preset Position Calibration

(1) Image Pixel Condition

Referring to the requirements of artificial intelligence analysis based on image processing, the road area in the image should be located in the middle of the image and occupy more than 60% of the image space, and the size of the vehicle target in the image should be no less than 400*400 pixels. Among them, the pixel scale of 400*400 occupied by the vehicle target in the image is regarded as the minimum pixel scale for target recognition.

(2) Imaging Model Construction

The projection relationship of the object in three-dimensional space to the imaging plane is the imaging model, as shown in Figure 2, the camera preset position and milepost matching using analytical geometry and trigonometry to determine the spatial relationship between the physical coordinates of the ground target and its imaging pixel coordinates.

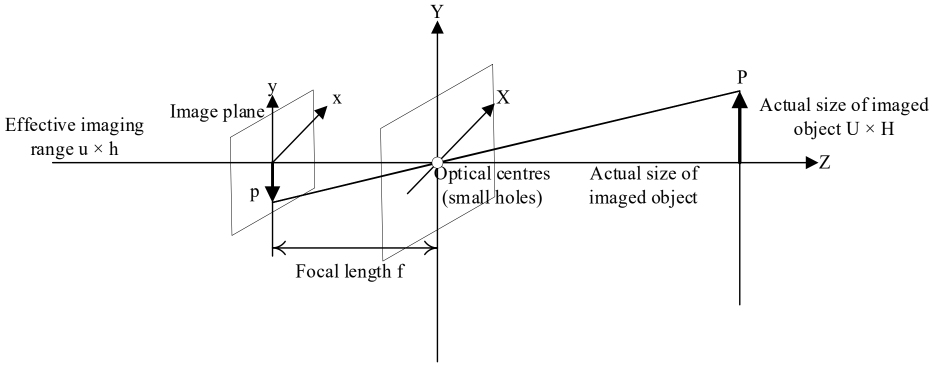


Fig. 2: Camera imaging model

The following conditional assumptions are made in the model: ignore the error caused by the road tilt, the error caused by internal conversion such as grating, the system error of the imaging principle model, the positional offset error in the lens rotation process, the computational accuracy is taken as 0.1, and all the system and model error terms of this model are summarized as the error term parameter $o(\delta)$. According to Figure 2, the camera distance dis_0 is inverted by the simplified focal length calculation formula, and the calculation is shown in equation (1).

$$dis_0 = \frac{U \cdot f}{u} + o(\delta_1) \text{ or } dis_0 = \frac{H \cdot f}{h} + o(\delta_2) \tag{1}$$

where dis_0 is the actual distance between the target and the monitoring dome, unit m; U is the actual height of the target, unit m; h is the imaging width of the target, unit mm; H is the actual width of the target, unit m; u is the imaging height of the target, unit mm; f is the focal length of the camera, unit mm; $o(\delta_1)$, $o(\delta_2)$is the error term caused by the error under the conditions of this hypothesis, unit m.

(3) Calculation of the distance to cover the road surface

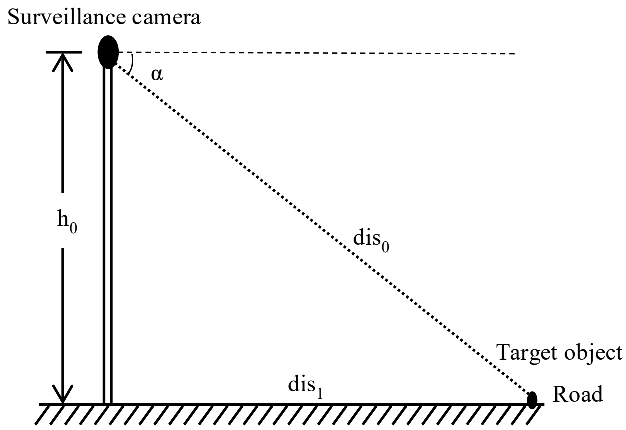


Fig. 3: Main view of the position of the surveillance dome in relation to the road surface

The main view of the surveillance dome in relation to the road position is shown in Fig. 3. By analyzing the analytical geometry of the main view, the linear distance of the coverage dis_1 is inverted using the trigonometric relation equation of the pitch angle α, which is calculated as shown in equation (2).

$$dis_1 = \sqrt{dis_0^2 - h_0^2} + o(\delta_3) = h_0 * \tan(\alpha - \alpha_0) + o(\delta_3) \tag{2}$$

where dis_1 is the theoretical coverable range of the monitoring dome, unit m; h_0 is the initial height of the monitoring dome, unit m; α_0 is the initial angle of the installation, unit °; $o(\delta_3)$ is the error term caused by this assumption condition, unit m.

Within a small range of road segments near the surveillance camera, if the road does not have significant substantial curvature, without taking into account the impact of roadside trees and other debris, the set of effective coverage stakes for video monitoring of road segments oriented to $[K - dis_1, K + dis_1]$, where K is the value of the mileage stakes of the surveillance camera itself.

2.2. Pre-positioning and Milepost Matching Technology

The process of camera preset position and milepost matching technology is shown in Figure 4. Firstly, it is necessary to split the video surveillance coverage into a number of road sections, calculate the camera limit preset position and intermediate preset position corresponding to each road section, and establish a matching relationship between the preset position and latitude/longitude; secondly, establish the matching relationship between mileage stake number and latitude/longitude data; finally, take latitude/longitude as the intermediate node to match the camera's preset position with the mileage stake number, and establish the matching relationship between the preset position and the mileage stake number.

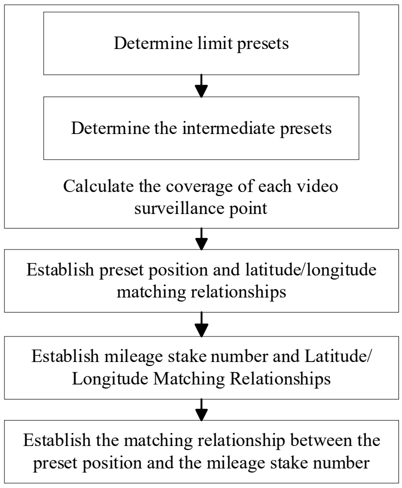


Fig. 4: Matching Flowchart

According to the above analysis, a two-dimensional geodetic coordinate system is established, with the x -axis being the direction of the positive extension of the road surface and the y -axis being perpendicular to the direction of the road surface, as shown in Figure 5. The horizontal angle of the calculation function is supplemented and adjusted to realize one-to-one matching of the three parameters of latitude, longitude and camera preset position.

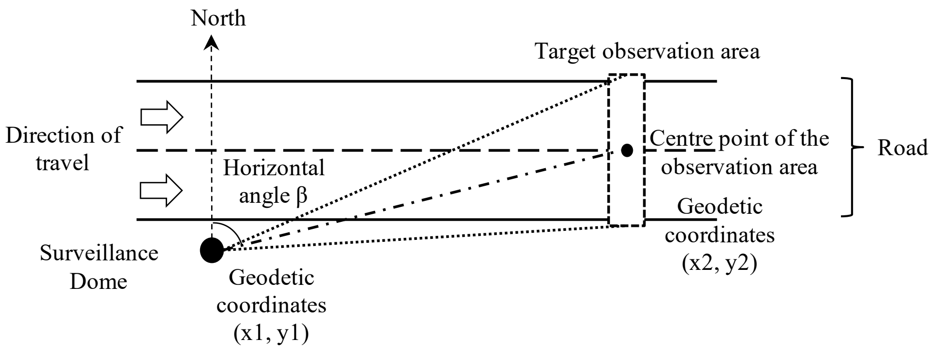


Fig. 5: Top view of surveillance dome with target observation area

The matching relationship between latitude and longitude and the camera preset position is obtained by analyzing the top view with analytical geometry and using the trigonometric relation equation for the horizontal angle β, as shown in equation (3).

$$\beta = arctan\left|\frac{x_1-x_2}{y_1-y_2}\right| - \beta_0 + o(\delta_4) \tag{3}$$

where (x_1, y_1) are the latitude and longitude coordinates of the spherical machine in the geodetic coordinate system; (x_2, y_2) are the latitude and longitude coordinates of the center point of the observation area; β_0 is the initial angle of the installation in °; and $o(\delta_4)$ is the error term caused by this assumption.

In practice, the coordinates of the observation center point are generally unknown, and the angle between the roadside camera and the horizontal line is sufficiently small, so β can also be approximated by dis and the road width N as shown in Equation (4).

$$\beta = arctan\left|\frac{dis}{kN}\right| - \beta_0 + o(\delta_4) \tag{4}$$

where k is the number of lanes, N is the motorized road width, generally taken as 3m, β_0 is the initial angle of the installation, unit °; $o(\delta_4)$ is the error term caused under this assumption.

Combining the above analysis, the matching relationship between camera preset position and pile number based on the imaging principle is calculated as shown in Eq. (5) and Eq. (6).

$$dis = R \times arccos[cos(y_0) \cdot cos(y) \cdot cos(x_0 - x) + sin(y_0) \cdot sin(y)] \tag{5}$$

$$\begin{cases} \alpha = arctan\frac{dis}{h_0} - \alpha_0 + o'(\delta_1) \\ \beta = arctan\left|\frac{x_1 - x_2}{y_1 - y_2}\right| - \beta_0 + o'(\delta_2) \text{ or } \beta = arctan\left|\frac{dis}{kN}\right| - \beta_0 + o'(\delta_2) \\ f = \frac{u \cdot dis \cdot cos\,\alpha}{U} + o'(\delta_3) \text{ or } f = \frac{h \cdot dis \cdot cos\,\alpha}{H} + o'(\delta_4) \end{cases} \tag{6}$$

In the formula, the intermediate preset position should be set according to the actual need. Generally, the intermediate preset position can be calculated and the preset position parameter can be set according to the distance of every 100m, i.e., the distance dis is gradually pushed in accordance with 100m, 200m and 300m until the limit preset position is reached.

Based on the imaging principle of the camera preset position and mileage stakes matching technology in the theory is practicable, but by the influence of the system error, but also need to correct the pitch angle, plane rotation angle and focal length parameters of the actual test.

3. Highway Precision Positioning Video Monitoring System

3.1. Overall System Design

A schematic diagram of the highway precise location video monitoring system is shown in Figure 6.

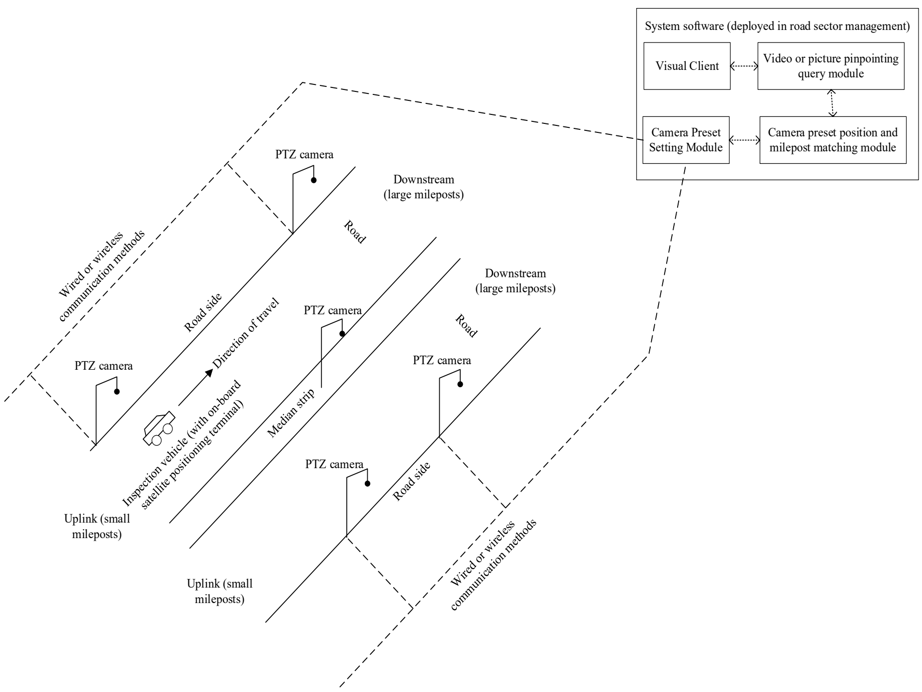


Fig. 6: Video monitoring system for precise positioning of highways

(1) Hardware Composition

① PTZ camera

PTZ camera is generally installed on the side of the highway, the central barrier on the fixed pole, the installation height is generally 8 to 12 meters, configured with a PTZ support camera horizontal rotation, up and down tilt movement and optical zoom control of the lens, the spacing between neighboring PTZ cameras for hundreds of meters to several kilometers, while the PTZ camera installation location of the mileage stake, latitude and longitude is determined.

② Vehicle-mounted satellite positioning terminal

Vehicle-mounted satellite positioning terminal supports portable mounted on the inspection vehicle, supports real-time access to the latitude and longitude information of the driving position of the inspection vehicle, the system through the vehicle-mounted satellite positioning terminal provides the latitude and longitude information on the calculation of the camera preset position for verification and correction.

(2) Software Composition

① Camera Preset Setting Module

Access PTZ camera video or pictures, based on the imaging principle, to obtain the camera preset position and the latitude and longitude of the road section it shoots the matching relationship between the camera preset position and the latitude and longitude of the matching relationship between the establishment of the camera preset position and the latitude and longitude of the table.

② Camera Preset and Milepost Matching Module

According to the conversion relationship between latitude and longitude and milepost number, it supports to convert the latitude and longitude range data of the road section photographed by each camera preset position to the milepost number range data of the road section photographed, and establishes a table of matching relationship between camera preset position and milepost number.

③ Video or picture precise positioning query module

It interacts with the camera preset position and milepost number matching module and receives the milepost number input by the business personnel through the visualization client, and automatically schedules the PTZ camera to accurately locate and focus on the road section of the queried milepost number for filming.

By matching the preset position of PTZ camera with the milepost number, it realizes the precise positioning query of video or picture of the corresponding road section by the business personnel according to the milepost number, which significantly improves the management efficiency of the highway industry.

3.2. Highway Precision Positioning Video Monitoring Methodology Process

Based on the above highway accurate positioning video monitoring system, the flow of the proposed highway accurate positioning video monitoring method is shown in Fig. 7.

Fig. 7: Highway Precision Location Video Monitoring Methodology Process

First, the camera preset position setting module calculates the camera preset position parameters through the matching technology of the camera preset position and the stake number, and obtains the camera preset position and latitude/longitude matching relationship table; the camera preset position and latitude/longitude matching relationship table is inputted into the camera preset position and mileage stake number matching module, and in accordance with the conversion relationship of latitude/longitude and mileage stake number, the camera preset position and mileage stake number matching relationship table is obtained.

Secondly, the camera preset position and mileage stake matching relationship table obtained is verified by inspecting the vehicle to determine the error parameters in the matching technology formula (1) to (6) of the camera preset position and stake.

(1) Driving an inspection vehicle equipped with a vehicle-mounted satellite positioning terminal, traveling from small to large direction by milepost number, and sending the latitude and longitude information of the current driving position of the inspection vehicle to the camera preset position setting module in real time.

(2) Combining the latitude and longitude information of the PTZ camera installation location, scheduling the PTZ camera closest to the current driving position of the inspection vehicle to capture video or pictures. With the driving process of the inspection vehicle, scheduling PTZ cameras to shoot videos or pictures one by one, carrying out deep learning-based target recognition and tracking of the inspection vehicle, with the inspection vehicle as the target, when the inspection vehicle meets the minimum pixel scale for target recognition, using the principle of camera imaging to automatically calculate the farthest distance of the inspection vehicle from the PTZ camera.

① Randomly select the roadside camera as the target to be measured, according to the position of the inspection vehicle in the video or picture and the occupation of the pixel scale relationship, fine-tune the PTZ camera up and down pitch angle α, to ensure that the inspection vehicle in the middle of the video or picture position, and the occupation of the pixel scale = the target recognition of the smallest pixel scale, at this time, the PTZ camera selected by the PTZ camera horizontal rotation β, the up and down tilt angle of α, as well as the lens optical zoom parameter f, that is, the limit of the pre-set position;

② These presets are recorded at intervals of 100 meters within the limit preset range, sorted by preset 1, 2, 3..., while 30%-40% of the presets within the limit presets are randomly selected as the presets to be examined;

③ According to the selected preset position, first in accordance with the above preset position setting method, and combined with the actual driving distance of the inspection vehicle, automatically adjust the PTZ camera gimbal horizontal rotation angle, up and down tilt angle of movement, if you can ensure that the inspection vehicle in the middle of the shooting video or picture position, and occupying the pixel scale ≥ the minimum target recognition pixel scale, then complete the verification of the preset position, record the camera preset position at this time of the parameter;

④ When a randomly selected preset position at an interval of 100 meters within the farthest distance covered by the camera is verified by the inspection vehicle, a new camera preset position with latitude/longitude match is formed.

(3) Correct the original table according to the new camera pre-position and latitude/longitude matching relationship, or input the new camera pre-position and latitude/longitude matching relationship table into the camera pre-position and milepost number matching module, and correct the original table according to the new camera pre-position and milepost number matching relationship.

Finally, the business personnel input the milepost number into the video and picture precise positioning query module through the visualization client, and according to the verified camera-milepost number matching relationship table, dispatch the PTZ camera closest to the input milepost number, and use the camera preset position that matches the input milepost number to shoot videos or pictures, and precisely locate and query the videos or pictures of the corresponding milepost number.

4. Calculus Analysis

4.1. Data Sources

Currently commonly used PTZ cameras are mostly 4 megapixel high-definition dome, support for 360 ° horizontal rotation, -20 ° ~ 90 ° automatic flip, so do not take into account the installation angle limitations, the calculation of the theoretical coverage of the road distance range. Assuming that the camera target surface for the 1/1.8-inch CCD sensor, target surface size of 7.2 * 5.4 mm, focal length of 6 ~ 240 mm auto-focus, installed on a 12-meter pole, the target is a standard car (size 3.8 * 1.8 * 1.5 meters), considering the car in the image of the limit of the state of tilt, the target car according to 3.8 * 3.8 meters. The basic requirement for a small car to be clearly visible is not less than 400*400 pixels. According to the imaging principle calculation formulas (1) and (2), it can be seen that,

$$dis_0 = min\left[\frac{U \cdot f}{u} + o(\delta_1), \frac{H \cdot f}{h} + o(\delta_2)\right]$$
$$= min\left(\frac{3800 \times 240}{400 \div \sqrt{\frac{4000000}{7.2 * 5.4}}}, \frac{3800 \times 240}{400 \div \sqrt{\frac{4000000}{7.2 * 5.4}}}\right) + o(\delta)$$
$$\approx 729600(\text{mm}) + o(\delta) \approx 729.6\text{m}$$
$$dis_1 = ({dis_0}^2 - {h_0}^2)^{0.5} + o(\delta_3)$$
$$= (729.6^2 - 12^2)^{0.5} + o(\delta)$$
$$\approx 729.5 \approx 730\text{m}$$

Therefore, the theoretical maximum roadway distance range that can be covered by the surveillance dome, i.e., the limit preset position is about 730 meters on one side.

The video surveillance can cover the roadway distance range is split, for each video point location upstream, downstream between the limit preset position observation range, in accordance with the adjacent preset position shooting images between the cross range of roadway monitoring sufficient requirements, one by one calibration of the intermediate preset position. Latitude and longitude as the intermediate nodes will be split for each preset position and mileage stake number to establish the corresponding calculation relationship, assuming that the camera is installed at K1, the initial pitch angle of 0 °, the initial horizontal angle of 0 °, the highway is a bi-directional six-lane road, according to the calculation of the formula (1) ~ (6) calculated in accordance with the Table 1 shown in. Finally, we get the camera parameter information of all available preset positions within the video surveillance coverage.

Table 1: Calculation table for preset position

Distance dis/m	Pitch angle α /°	Horizontal angle β /°	Focal length f/mm
100	6.8428	84.8572	32.8178
200	3.4336	87.4234	65.6356
300	2.2906	88.2816	98.4534
400	1.7184	88.7111	131.2712
500	1.3748	88.9688	164.0890
600	1.1458	89.1406	196.9068
700	0.9821	89.2634	229.7246

In practice, the calculation example in the paper adopts the Nantong section of National Highway 204, where the installation height of the roadside PTZ camera is h=12 meters, the initial horizontal angle α=0°, and the initial pitch angle β=0°. In addition, the size of the inspection vehicle is 3.8*1.8*1.5 meters, and the pixel scale of the inspection vehicle in the picture is equal to 400*400.

4.2. Evaluation Indicators

(1) Mean Square Error (MSE), Root Mean Square Error (RMSE): when calculating the preset bits, the error is expressed by the square of the distance between the calculated value and the true value, as shown in equations (7) and (8).

$$MSE = \frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2 \quad (7)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2} \quad (8)$$

(2) Mean Absolute Error (MAE): when calculating the preset bits, the error is expressed by the absolute value of the distance between the calculated value and the true value, as shown in equation (9).

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|y_i - \hat{y}_i| \quad (9)$$

(3) R Squared (R^2): the degree of fit between the calculated value and the real value when calculating the preset bit, the range of values is 0~1, and the maximum value of 1 indicates complete fit, and this value is used in the text as the accuracy of the calculated value, as shown in equation (10).

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(\bar{y}_i - y_i)^2} = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2/n}{\sum_{i=1}^{n}(\bar{y}_i - y_i)^2/n} = 1 - \frac{MSE}{D(y_i)} \quad (10)$$

where $D(y_i)$ is the variance of the true value.

(4) Monitoring Response Time (Time): Evaluates the response time of known mileage stakes to adjust the camera to capture video images of the corresponding roadway location by manual or automated means. Faster response time is an important indicator of real-time monitoring and response to emergencies, which is expressed as the time consumed from the start of the input of the pile number command to the selected camera to complete the steering to the preset position of the corresponding pile number. Correspondingly, for manual operation, the time is expressed as the time consumed from the time when the industry manager receives the pile number query instruction to the time when the selected camera is manually operated and completes steering to the preset position of the corresponding pile number.

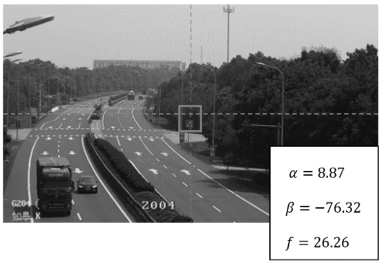
4.3. Case Study

Randomly select 100 mileposts from K724+688 to K808+835 in the Nantong section of National Highway 204 and input them into the camera preset position matching algorithm; By default, the camera preset parameters adjusted manually are the correct preset parameters; Then statistically compare the preset parameters calculated by the camera preset matching algorithm with the manually-operated adjustment of the preset parameters. The results of the calculation of the average error of the preset parameters calculated by the camera preset matching algorithm are shown in Table 2, and the average R^2 of the three camera preset parameters reaches 87%.

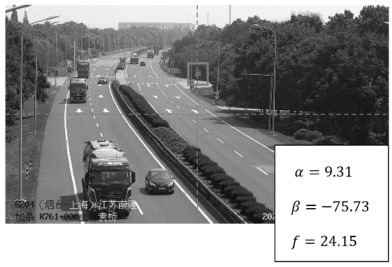
Table 2: Indicators for evaluating the results of calculations of the methodology for video monitoring of roads (precise positioning)

	RMSE	MAE	R^2
Pitch angle α	0.1931	0.4217	0.8673
Horizontal angles β	0.2025	0.3987	0.9057
Focal length f	0.2584	0.5217	0.8364
Average	0.2180	0.4474	0.8698

To further verify validity, select traffic signs with known mileage pile numbers in Nantong section of National Highway 204 as test targets. Industry managers use Highway Accurate Location Video Monitoring System to query video images at corresponding traffic signs and compare with those at manually operated scheduling traffic signs without using the system. Output of industry managers using the system is shown in Fig. 8(a), i.e., by inputting target mileage stake, system automatically determines nearest camera to stake and calculates preset position of corresponding camera using optimal shooting parameters according to matching algorithm, and quickly outputs corresponding regional images, whole query process takes about 5-6 seconds. Without using the system, manual operation scheduling of video image at traffic sign as shown in Fig. 8(b), industry managers based on experience in existing monitoring points of view for manual point comparison, then select most appropriate camera and preset position, and ultimately get corresponding area picture. Whole operation process takes about 30 seconds.



(a) Examples of methods in the text



(b) Examples of manual operations

Fig. 8: Comparison of examples of National Highway 204 Nantong Section (G204 Ru Gao K761+000).

By comparing Fig. 8(a) and Fig. 8(b), it can be seen that there is a slight deviation between the output pics of using the highway accurate positioning video monitoring system and those of not using the system and manual scheduling, but they effectively cover the queried mileage pile numbers. In terms of monitoring response time indicators, the efficiency of outputting pics using the system is significantly higher than that of manual monitoring by more than 5-6 times, proving that the method can significantly improve operational efficiency and reduce time cost in practical applications.

5. Conclusion

In the paper, a highway video monitoring method for precise positioning based on active spatiotemporal control is proposed, and a highway accurate positioning video monitoring system and process are constructed. The main research results are as follows:

(1) According to the existing or new high-definition camera technical specifications, the limit preset position and intermediate preset position setting methods for each video point are clarified, and the camera calibration technology for the full coverage of video monitoring of road sections is formed.

(2) The matching relationship between the camera preset position and the route stake number has been established, realizing the function of automatically scheduling the PTZ camera to accurately locate to the road section for shooting by inputting the range of the route stake number, and forming the matching technology between the camera preset position and the mileage stake number.

(3) Based on customized active spatiotemporal control query conditions such as time, mileage stake number, etc., the highway accurate positioning video monitoring was realized, and the implementation was verified in the Nantong section of National Highway 204. The results show that the method not only has a higher accuracy rate compared with manual operation adjustment, the average R^2 of the three camera pre-positioning parameters reaches 87%, but also improves the efficiency by more than 5 times compared with manual monitoring in terms of monitoring response time.

The highway video monitoring method based on active spatiotemporal control proposed in paper comprehensively considers time and space info needs for road network inspection. It's an active, dynamic mode, taps potential of existing roadside HD facilities, effectively improves video monitoring precision, digitalization, and intelligent level of road network management and maintenance inspection, suitable for large-scale promotion and application.

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