Research on a novel train positioning method with a single image

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Abstract

Comprehensive train monitoring is an important infrastructure detecting facility that ensures normal operation of the high-speed railway. An accurate position is the basis of precise detection. A research on the autonomous train location method is of great theoretical and practical significance for the positioning of comprehensive monitoring train and enhancing the infrastructure detecting level of the existing line. Comprehensive train monitoring synchronizes all diagnosis parameters by sharing time and position. However, it cannot correct the odometer's accumulative error with the track circuit's insulator in high-speed railways. This paper presents a novel position correction method with a single image. It analyses the three dimensional (3D) camera projection model and its disadvantage. A simplification from the 3D to the one dimensional (1D) model is proposed. The actual distance between the landmark and the camera optical center is calculated with image coordinates of the landmark acquired by the camera fixed on top of the train. Then, the actual position of the train can be calculated with the pre-stored landmark position and the calculated distance. Both academic and experimental errors indicate that the position correction method with a single image can satisfy the train positioning requirement.

Keywords: train position, single image, projection model, one dimension simplification, landmark.

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1 Introduction

Odometry is a familiar method for vehicle location. However, there is a limitation of accumulative error for odometry. The track circuit's isolator is a traditional and effective way to correct accumulative error in railways. The track inspection car always locates at the tail-end of train. Hence, it cannot use the track circuit's isolator to correct the accumulative error of the odometer. Otherwise, the track inspection car needs to survey all railway lines, including lines without a track circuit (such as the Qing-Zang line, which is based on GSM-R). It is impossible for these lines to add devices to correct the odometer accumulative error at the target point only for the track inspection car that is running. So a novel correction position method at the target point with recognition of an existing landmark in an image is proposed in this paper.

Estimating the 3D pose and position of an object with an image is a key process and a kernel problem in machine vision applications. The advantages of wide range, the lack of intervention needed and high precision make image measurement applicable in many fields. Object positioning with images includes the process of 2D image projection and 3D reconstruction. Firstly, a 2D image of a 3D object in a real world coordinate is produced by the camera. Then, the 2D images can be analyzed and processed for 3D reconstruction and geometric measurement. The interior and exterior camera parameters are a precondition for calculating an object world coordinate in the 3D reconstruction process (Zheng [1]). These parameters are obtained by the calibration process of the camera. However, there is hard calculation load for the interior and exterior parameters [2, 3].

Sun and Wang [4] point out that position with a single image is the simplest and most convenient way for object position. It is not necessary to look for corresponding conjugate image points in binocular image pairs and it also not necessary to carry out a transformation between different coordinates. Ogawa et al. [5] proposed a self-positioning system using a digital mark pattern and a CCD camera. The horizontal distance from the mark pattern is measured using the ratio between the length and width of the mark pattern image. Lee et al. [6] proposed an algorithm to recognize and track the road lane by interpreting a 2D image to a 3D image by angle and position of the CCD camera. Fang et al. [7] proposed an algorithm for vision location on the condition of uncalibrated camera fixation and coplanarity. It gives the 3D calculation model, using the property of projective geometry.

For train position, we are only concerned about the longitudinal distance ahead of the train. We propose a 1D simple calculation model based on the 3D calculation model with camera fixation and coplanarity. It greatly reduces the computation load and gives the error analysis. In this paper, we firstly gives the 3D position model with a single image, then the 1D simplification and its error model is introduced. Finally, an experiment result on the railway field is used to validate this method.

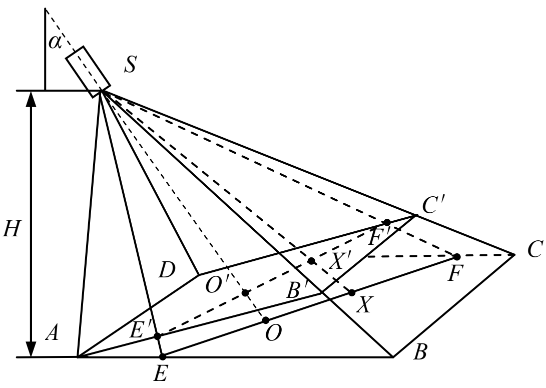

Figure 1: 3D positioning model of the camera.

2 Train positioning method with a single image

2.1 3D position model with a single image

In perspective projection, the straight line connecting the optical center and the image points is used to establish that the corresponding object point is not the one and only. The depth information cannot indicate in image. However, when a fixed camera takes pictures of objects on a plane, the plane provides a constraint in the direction of height. For train position, the objects on the ground can be deemed as coplanar to a certain extent. Under this condition, the points on the ground and on the image are corresponding one by one. Under the constraint of a fixed camera and coplanar image (to a certain extent), the position of an object can be achieved via the camera image so long as the relation between objects and images is determined.

Figure 1 shows the 3D positioning model of camera, in which H is the height from the projection center S to the ground, α is the angle between the optical axis and the vertical direction, ABCD is the camera's field of vision on the ground and AB′C′D is a virtual reference plane vertical to optical axis. The optical axis intersects with the ground level and virtual reference plane at points O and O′ respectively and X is the position of a landmark point on the ground. The virtual reference plane is not in geometric proportion to the ground plane. However, due to its being vertical to the optical axis, the virtual reference plane is in geometric proportion zoom to the image. So

$$\frac{E'X'}{O'X'}:\frac{E'F'}{O'F'}=\frac{E''X''}{O''X''}:\frac{E''F''}{O''F''} \tag{1}$$

where *E″O″X″F″* are points on the image corresponding to points *EOXF* on the ground plane respectively. According to the collinear equation and invariable cross ratio of central projection, we get eqn (2):

$$\frac{EX}{OX}:\frac{EF}{OF}=\frac{E'X'}{O'X'}:\frac{E'F'}{O'F'} \tag{2}$$

According to eqn (1) and (2), we can get

$$\frac{EX}{OX}:\frac{EF}{OF}=\frac{E''X''}{O''X''}:\frac{E''F''}{O''F''} \tag{3}$$

Eqn (3) shows the proportional relation between points *EOXF* on the ground and points *E''O''X''F''* in the image. In eqn (3), so long as the position of the pixels of landmark feature in the image is determined, the actual position of this landmark on ground will be worked out. Furthermore, the train position will be calculated.

However, while calculating with eqn (3), *EF* and *E''F''* must be known. They are intersection points of the extending lines of *OX* and *O''X''* with plane boundary respectively, which can be calculated by the equation group of two intersection lines. However, for each landmark point *X* and *X''*, *EF* and *E''F''* must be calculated once, which results in a heavy calculation load and long calculation time. This is not of advantage to real-time calculation.

2.2 1D simplification of the 3D model

When we position a train with an image, only the longitudinal position in the direction of train running is concerned. If the 3D model can be simplified into a 1D model, the calculation load and complexity will be reduced.

Figure 2 is the schematic diagram of 1D longitudinal positioning with a single image. In this diagram, the camera is fixed rigidly on the frontage top of the locomotive. Within a short distance in front of the locomotive, the position of the camera relative to the ground is determinate when ignoring the track gradient and outer rail super-elevation on the curve, where *H* is the height from the projection center *S* to the ground, α is the angle between the optical axis and the vertical direction, the vertical field angle of camera is θ and *P* is the vertical projection of the projection center *S* on the track plane. In the direction of train running, the nearest point in the field of vision corresponds to point *E* on the ground and the furthermost point in the field of vision corresponds to point *F* on the ground. In this figure:

$$\begin{cases} |PE| = L_1 = H\tan(\alpha-\theta/2) \\ |PF| = L_2 = H\tan(\alpha+\theta/2) \end{cases} \tag{4}$$

Therefore, the longitudinal field range of the camera is as follows:

$$L = L_2 - L_1 == H[\tan(\alpha+\theta/2)-\tan(\alpha-\theta/2)] \tag{5}$$

The distance from landmark *X* to point *P* is

$$|PX| = |PE| + |EX| = L_1 + |EX| \tag{6}$$

where |*EX*| means the distance from the target point to the nearest point in field of vision, which can be worked out according to the pixels coordinate of the landmark in the image.

In figure 2, γ is the angle between the projection ray of landmark X and the optical axis; X' is the projection of landmark X on the virtual reference plane; EF' is the projection of the virtual reference plane on the longitudinal 1D section. The distance on line EF' is in direct proportion to the distance of the corresponding point in the image. Therefore, the distance on the virtual reference plane can be represented as the pixels distance in the image. Assuming $O'X'$ is y, the direction of $O'F'$ is positive and the direction of $O'E$ is negative. Assuming $|SO'|=d$, $|PE|=L_1$, $|PF|=L_2$, $|O'E|=|O'F'|=\frac{|EF'|}{2}=W/2$, then

$$d=\frac{W/2}{\tan(\theta/2)}=\frac{W}{2\tan(\theta/2)} \tag{7}$$

In triangle $SO'X'$,

$$\gamma=\arctan\frac{y}{d}=\arctan\frac{2y\tan(\theta/2)}{W} \tag{8}$$

Therefore, the distance of landmark X to the projection point of camera P is as follows

$$|PX|=H\tan(\alpha+\gamma) \tag{9}$$

The real position of landmark X can be calculated with eqns (8) and (9).

2.3 Error analysis for the 1D simplification model

In eqn (9), the factors affecting error include: H, α and γ. The assumed height variation is ΔH. The variation of α and γ is integrated as angle variation $\Delta\gamma$. Therefore, the error formula is as shown in eqns (10) and (11).

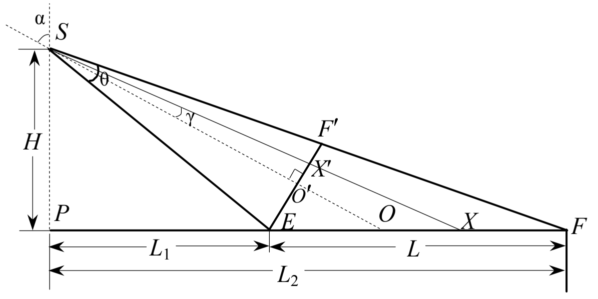

Figure 2: 1D positioning model with a single image.

$$
\begin{aligned}
\Delta L &= (H+\Delta H)\tan(\alpha+\gamma+\Delta\gamma) - H\tan(\alpha+\gamma) \\
&= H\tan(\alpha+\gamma+\Delta\gamma) - H\tan(\alpha+\gamma) + \Delta H\tan(\alpha+\gamma+\Delta\gamma) \\
&= \frac{H\tan(\Delta\gamma) + H\tan^2(\alpha+\gamma)\tan(\Delta\gamma) + \Delta H\tan(\alpha+\gamma) + \Delta H\tan(\Delta\gamma)}{1-\tan(\Delta\gamma)\tan(\alpha+\gamma)} \qquad (10) \\
&= H\tan(\Delta\gamma)\frac{1+\tan^2(\alpha+\gamma)}{1-\tan(\Delta\gamma)\tan(\alpha+\gamma)} + \Delta H\frac{\tan(\alpha+\gamma)+\tan(\Delta\gamma)}{1-\tan(\Delta\gamma)\tan(\alpha+\gamma)}
\end{aligned}
$$

Ignoring the infinitesimal of the second order in eqn (10), then

$$
\Delta L = \frac{H\tan(\Delta\gamma) + H\tan^2(\alpha+\gamma)\tan(\Delta\gamma) + \Delta H\tan(\alpha+\gamma)}{1-\tan(\Delta\gamma)\tan(\alpha+\gamma)} \qquad (11)
$$

In error equation eqn (11), there are two factors affecting the error: height and angle. The height variation mainly depends on two aspects: firstly, height variation would be caused by super-elevation of the outer rail while the train is passing a curve. In the Chinese railway, the maximal super-elevation on a single-line track is 125mm, and 150mm for a double-line track. The maximal super-elevation only appears on small curvature curves. Secondly, high variability would be caused by the swaying of the car body, but this value is less than that caused by super-elevation. Since the camera is fixed on the central line of the car body, considering the two factors comprehensively, it is assumed that the maximal height variation is 75mm.

As for angle variation, due to the camera being fixed rigidly with the car body, it will move together with the car body. So the affection on angle α by gradient and car body vibration can be ignored theoretically. The variation of angle γ between the landmark projection line and the optical axis is introduced by the quantization error of pixels. Assuming that the pixels quantization error is 1, the maximal angle error caused by boundary pixels is 0.025 degree. Therefore, for angle variation, only the variation caused by boundary pixels is considered.

Putting height and angle variation into eqn (11), the boundary error is 0.249m, which is the maximal theoretical error.

3 Experiment results

In order to verify the validity of the above-mentioned 1D simplified calculation model, MV-752 high-speed camera with 752×582 black and white pixels was adopted for the experiment, which has the maximal frame frequency of 350 frames per second. During the experiment, the height from the camera to the ground is *H*=2.81m, the visual field angle is $\theta = 14.3°$ and the angle between the optical axis and the vertical direction is $\alpha = 77.8°$, as a result, $L_1 = 8.00m$ and $L_2 = 31.80m$.

Figure 3 shows the picture taken during the test on the railway experiment, in which the white line on the right rail acts as a landmark point. The distance from the real point corresponding to the lower image boundary to the camera is 8m.

The distance from the first landmark to the corresponding lower image boundary point is 0.56m. There are in total 24 landmark points with 1m interval in the field of vision.

Table 1 shows the experiment result and the error of landmark points. The maximal error is -0.15m, which is within the range of error model analysis. The precision can meet the train positioning requirement.

4 Conclusion

This paper introduces a 1D simplification method for the 3D position model with a single image. The 1D calculation formula and its error equation are also deduced. Both the theoretical calculation and the experiment result on the railway show that this method has very high precision, and can meet the precision requirement of train position spot correction.

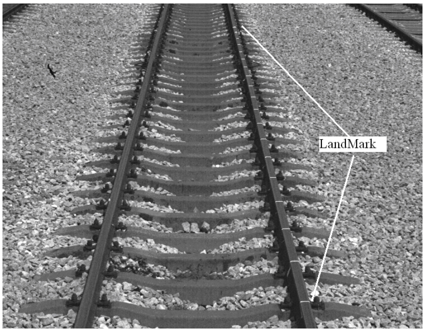

Figure 3: Picture with landmark on tracks.

Table 1: Measurement result and error of the 1D projection position model.

No.	row No.	measurement value(m)	actual value (m)	error(m)	No.	row No.	measurement value(m)	actual value (m)	error(m)
1	534	0.557	0.56	-0.003	13	113	12.481	12.56	-0.079
2	461	1.553	1.56	-0.007	14	98	13.506	13.56	-0.054
3	403	2.513	2.56	-0.047	15	85	14.479	14.56	-0.081
4	354	3.479	3.56	-0.081	16	73	15.456	15.56	-0.104
5	312	4.45	4.56	-0.11	17	62	16.427	16.56	-0.133
6	274	5.474	5.56	-0.085	18	51	17.480	17.56	-0.080
7	242	6.470	6.56	-0.09	19	42	18.410	18.56	-0.150
8	214	7.464	7.56	-0.096	20	33	19.408	19.56	-0.152
9	189	8.470	8.56	-0.090	21	24	20.483	20.56	-0.077
10	167	9.465	9.56	-0.095	22	16	21.510	21.56	-0.050
11	147	10.474	10.56	-0.084	23	9	22.470	22.56	-0.090
12	130	11.428	11.56	-0.132	24	2	23.494	23.56	-0.066

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