A CRITERION OF RADIAL DISTORTION ON STRUCTURE FROM MOTION WITH CONSUMER-GRADE CAMERAS

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Abstract
Images from consumer-grade cameras typically contain significant radial distortions, resulting in less accurate photogrammetry results generated using Structure from Motion (SfM). It is prone to reconstruct inaccurate scene points, becoming the so-called doming effect. The main reason is that in bundle adjustment, the last step of SfM, radial distortion is insufficiently estimated even though self-calibrating bundle adjustment was carried out. This paper designed a criterion to measure the radial distortion before SfM calculation, called Criterion on Radial Distortion (CRD). Firstly, the feature points were extracted and matched on the image; then, the image was divided into circular blocks, and the fundamental matrices were estimated by the matching points in different ring sub-blocks; finally, the difference between these fundamental matrices was used to reflect the radial distortion. Experiments on simulation data show that CRD can accurately reflect the radial distortion, which verifies its validity. Using actual UAV image data to conduct SfM experiments, CRD is consistent with the self-calibration results of Agisoft Metashape. After evaluating the accuracy of the elevation of scene points, it verifies its necessity for SfM.

KEY WORDS: Criterion on Radial Distortion (CRD), Fundamental Matrix, Structure from Motion (SfM), self-calibrating bundle adjustment.

1. INTRODUCTION

Structure from Motion (SfM, Xiao et al., 2021) can simultaneously obtain image orientation parameters and 3D point coordinates of the scene. Because of its high degree of automation, SfM has been a powerful tool used in UAV mapping, image-based 3D reconstruction, and robot vision positioning.

Today, consumer-grade cameras have been widely used for collecting images. Large radial distortions of consumer-grade cameras often influence these resulting images. Dealing with these images with significant distortion typically leads to low-precision SfM results. A sample case is in low-cost UAV photogrammetry (Jiménez-Jiménez et al., 2021). It is prone to reconstruct inaccurate scene points, becoming the so-called doming effect (Jiménez-Jiménez et al., 2021; Meinen and Robinson, 2020), i.e., flat scenes often become curved. The main reason is that in bundle adjustment, the last step of SfM, radial distortion, is insufficiently estimated even though self-calibrating bundle adjustment was carried out. Thus, it leads to low-precision SfM results. Therefore, for consumer-grade cameras, it should be careful of radial distortion for obtaining high-precision SfM results.
Traditional SfM pipelines do not consider radial distortion until the final bundle adjustment. It is very difficult to set a reasonable distortion model because of the lack of prior radial distortion. Therefore, this paper strives to propose a practical criterion of radial distortion and embed it into an SfM pipeline for verification. To the best of our knowledge, this is the first work to propose criterion of radial distortion in the community of SfM.

2. METHOD

This paper proposed a criterion to measure the radial distortion before SfM calculation, called Criterion on Radial Distortion (CRD). The greater the degree of radial distortion, the farther the fundamental matrix deviates from the actual value (Fan et al., 2021). Suppose the fundamental matrix estimation is carried out by the central area and other areas, respectively. And then, the difference between the two fundamental matrices can reflect the degree of radial distortion of the image, which is the main idea of our method. We then embedded our CRD computation into a traditional SfM, becoming a new pipeline for dealing with UAV images, as is shown in figure 1.

In figure 1, feature extraction and matching and geometric filtering are first carried out to obtain the point correspondences of every match image pair. As one of the robust strategies, a maximum spanning tree is used to select the best match pairs to reduce the effect of mismatched point correspondences. This strategy often helps avoid using the mismathed image pairs. For each one, we compute a CRD, and then for these selected pairs, we get an average one, which makes the CRD computation more robust.

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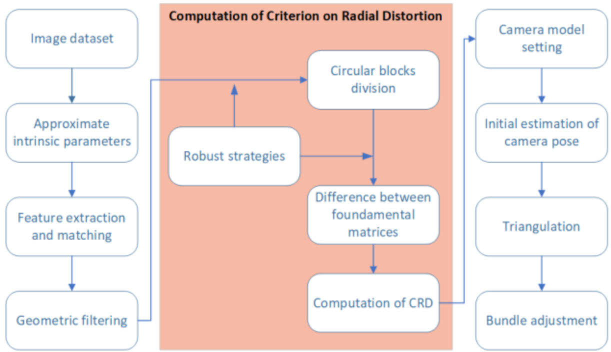


Fig. 1 Flowchart of the new global SfM by embedding the CRD

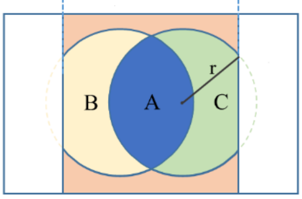


Fig. 2 Example of sub-blocks of the overlapping aera

For the computation of CRD in one matched image pair, point correspondences are already known. Then the matching points in different ring sub-blocks; finally, the difference between these fundamental matrices were used to reflect the radial distortion. To give more details, the overlapping area, i.e., the bounding box of the point correspondences (Ω_S), is denoted as S. Then circular blocks division is to cut S into three sub-blocks, which can be denoted as A, B, C, see figure 2. The point correspondences of the three sub-regions can be defined as $\Omega_A, \Omega_B, \Omega_C$. According to the characteristics of radial distortion, the feature points in the central area of the image are subject to little radial distortion, so the re-estimated fundamental matrix from correspondences of A aera is hardly affected by radial distortion; we get F_{new}. On the contrary, B or C aera is heavily affected by lens distortion, which leads to the originally estimated fundamental matrix F of the whole overlaaping aera S is also affected by radial distortion. Thus, the difference between F and F_{new} can reflect the degree of the radial distortion.

The next question is how to measure the difference and make it represent the CRD. For one inlier point correspondence $(x_{\Omega_S,L}; x_{\Omega_S,R}) \in \Omega_S$, it is known that the error of $x_{\Omega_S,R}^T\ F\ x_{\Omega_S,L}$ is less than a threshold among RANSAC. If we replace F with F_{new}, i.e., having $x_{\Omega_S,R}^T\ F_{new}\ x_{\Omega_S,L}$, it will be an offset with the unit of the pixel. For all inlier point correspondences of this match pair, we can represent the difference between F with F_{new} by

$$D(F_{new}, F) = \frac{\left(\sum_{i=1}^{n} \frac{\left|x_{\Omega_S,R}{}^T \cdot F_{new} \cdot x_{\Omega_S,L}\right|}{\sqrt{a^2+b^2}}\right)}{n} \quad (1)$$

where n is the number of the inlier point correspondences of one match image pair. Note that another robust strategy here removes the correspondences along the epipolar line from the inlier set. We further compute CRD by counting all selected image pairs, then we have

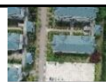
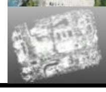
$$CRD = \frac{\sum_{i=1}^{m} D(F_{new}, F)}{m} \quad (2)$$

3. RESULTS AND DISCUSSION

To verify the rationality and necessity of this criterion, this paper uses simulated data and actual UAV image data to conduct experiments. This experiment simulates nine groups of data with different degrees of radial distortion. And then, the CRD of the nine data groups can be calculated according to formula (2). It can be found that the CRD increases proportionally with the increase of the radial distortion of the simulated data, which verifies that the radial distortion index proposed in this paper can reflect the degree of radial distortion of different data.

For UAV real datasets, the data used in this experiment are nadir images captured by five groups of drones equipped with different cameras. These scenes are complex and diverse, and control points are also provided. Table 1 shows examples of 5 image sets and sparse point clouds of 3D scenes.

Table.1 Sample UAV images and the corresponding scene points

Name	P395	P316	P219	P92	P475
Iamge					
Scene					

Since the actual radial distortion of these five image sets is unknown, this paper uses the radial distortion calibration results of the commercial software Agisoft Metashape as a reference. Figure 3 describes the relationship between the radial distortion of the CRD and the calibration results of Agisoft Metashape. The blue bar graph represents the result of Agisoft Metashape, and the yellow bar graph is the CRD index obtained by the algorithm in this paper. The radial distortion of the five groups of data calibrated by Agisoft Metashape is consistent with the CRD index proposed in this paper, which further proves that the CRD index proposed in this paper can reflect the actual degree of radial distortion of the image.

To verify the necessity of this criterion, this experiment uses four different radial distortion model pairs to perform self-calibration SfM. Through experiments, it is found that the plane accuracy obtained using different distortion models is relatively consistent, but the elevation accuracy shows significant differences, that is, the "doming effect." Therefore, in this paper, the deviation between the estimated value of the checkpoint elevation and the actual value will be averaged as the accuracy of the self-calibration SfM. The experimental results are shown in Table 2. The radial distortion model is based on the Brown model. The K1 model in Table 2 indicates that only the K1 coefficient is used. Similarly, the K2 model indicates that the K1 and K2 coefficients are used, and so on. The bold value represents the result with the highest elevation accuracy, which indicates that when the CRD is higher, the degree of radial distortion is more significant. More radial distortion parameters must be used in the SfM calculation to obtain better elevation accuracy. Therefore, the CRD can truly reflect the degree of radial distortion of the image, which can be used as a priori information in the self-calibration SfM to adjust the radial distortion model and effectively improve the accuracy of the self-calibration SfM.

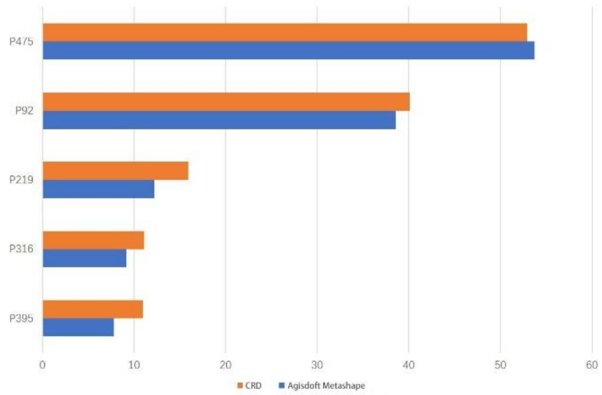


Fig.3 The calibration result of dataset P92 between CRD and Agisoft Metashape

Table.2 The relationship between CRD and the optimal radial distortion model

dataset	CRD	Error of elevation of check points/m			
		K1	K2	K3	K4
P395	10.9482	**0.0012**	0.0066	0.0278	0.0319
P316	11.1075	**0.0307**	0.0994	0.1276	0.1331
P219	15.9303	0.1681	**0.1275**	0.2016	0.2005
P92	40.0784	1.1900	0.1993	0.0531	**0.0245**
P475	52.9537	0.1130	0.0601	0.0417	**0.0213**

4. CONCLUSION

In the low-cost UAV photogrammetry community, the used consumer-grade cameras contain significant radial distortion. It typically leads to low-precision SfM results because radial distortion is insufficiently estimated in the self-calibrating bundle adjustment. In this paper, we proposed a practical criterion of radial distortion and embedded it into the traditional SfM pipeline. Experiments show that this criterion accurately reflects the degree of actual radial distortion. Its necessity for SfM is also verified by evaluating the accuracy of elevation of scene points. In future work, though calculating this criterion for many actual images, we will enable adaptive selection of distortion model to improve the practicality of this method.

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