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Calibration and Image Restoration for the Beam Profile Measurement System

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ABSTRACT :

The beam profile parameters are one of the most important parameters which represent the beam quality. The transverse beam profile parameters are closely related to the beam tuning and optimization of the cyclotron. In order to improve the precision and efficiency of beam profile measurement system, A calibration method has been implemented for the calibration of the imaging system. Moreover, a new image noise reduction algorithm has been developed to improve the image quality, and then to improve the measurement accuracy of the beam profile parameters. In addition, two image restoration algorithms have also been adopted to eliminate the effects of defocusing blur. The experiment results show that the calibration of the imaging system enable the system to provide quantitative information for beam diagnosis. The image noise reduction and restoration algorithm greatly improve the measurement accuracy of beam profile parameters.

Introduction

The beam profile parameter is one of the important parameters, which represents the beam quality. The performance of the accelerator and the safe and stable operation are closely related to the transverse beam distribution.

The measurement of beam profile parameters can provide an important basis for the debugging and commissioning of the accelerator and the improvement of beam quality.

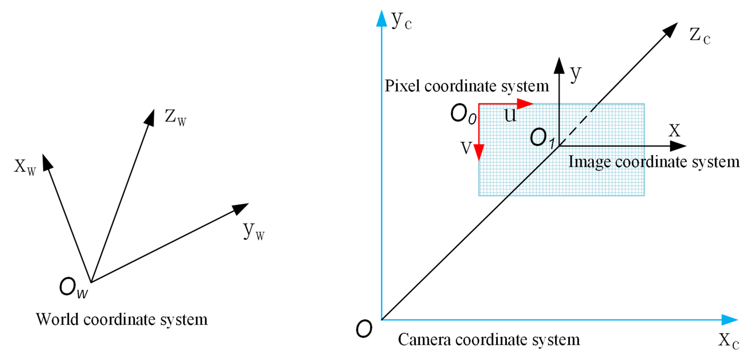
The main factors leading to the image degradation of the scintillator detector include：

a) The image distortion caused by the aberration and nonlinear distortion of the imaging system;
b) Various noises introduced by the imaging system and image transmission process;
c) Defocus blur caused by inaccurate focus of the camera.

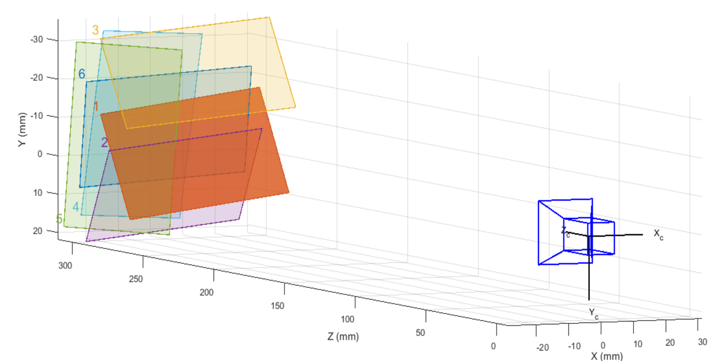
Calibration of the Imaging System

The conversion relationship between the pixel coordinate system and the world coordinate system:

$$z_c \cdot \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} \frac{1}{dx} & 0 & u_0 \\ 0 & \frac{1}{dy} & v_0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} f & 0 & 0 & 0 \\ 0 & f & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \cdot \begin{bmatrix} \boldsymbol{R}_{3\times3} & \boldsymbol{T}_{3\times1} \\ \boldsymbol{0} & 1 \end{bmatrix} \cdot \begin{bmatrix} x_w \\ y_w \\ z_w \\ 1 \end{bmatrix} = \begin{bmatrix} f_x & 0 & u_0 & 0 \\ 0 & f_y & v_0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \cdot \begin{bmatrix} \boldsymbol{R}_{3\times3} & \boldsymbol{T}_{3\times1} \\ \boldsymbol{0} & 1 \end{bmatrix} \cdot \begin{bmatrix} x_w \\ y_w \\ z_w \\ 1 \end{bmatrix} = \boldsymbol{M_1 M_2 X_w}$$



The relationship between four coordinate systems



The schematic diagram of camera calibration

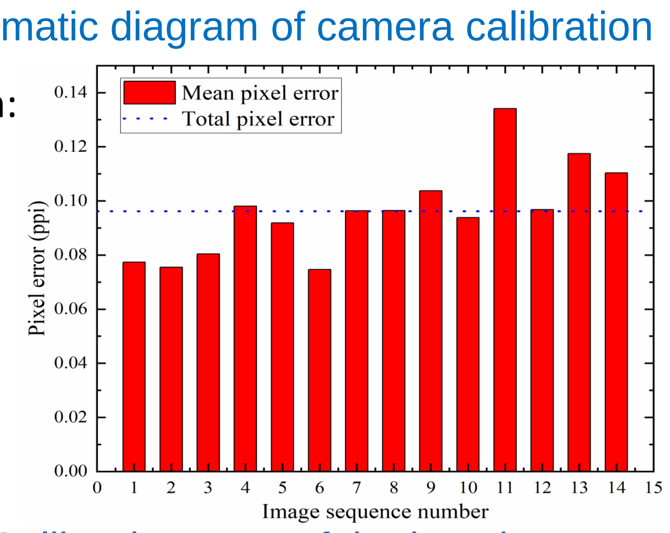
The radial distortion is corrected by the Taylor series expansion:

$$x_c = x(1 + k_1 r^2 + k_2 r^4 + k_3 r^6)$$
$$y_c = y(1 + k_1 r^2 + k_2 r^4 + k_3 r^6)$$

The tangential distortion is corrected by:

$$x_c' = x + [2p_1 y + p_2(r^2 + 2x^2)]$$
$$y_c' = y + [2p_2 x + p_1(r^2 + 2y^2)]$$

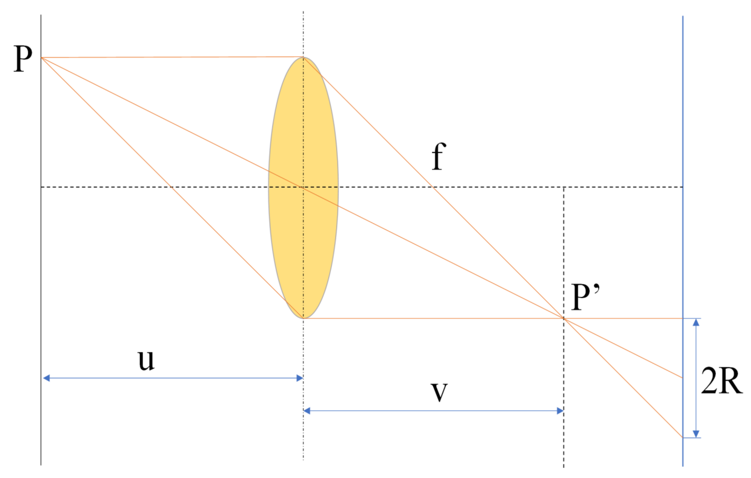
Through the calibration, the internal parameter matrix of the camera and the distortion coefficients can be calculated.



Calibration error of the imaging system

Image Degradation Model

Impulse noise is a common multiplicative noise caused by the external interference to image sensors and transmission channels.



Optical path diagram of the defocusing imaging system

The ideal imaging formula

$$\frac{1}{f} = \frac{1}{u} + \frac{1}{v}$$

However, if the focal length, object distance and image distance in the imaging system do not satisfy the imaging formula, a point on the original image will become a uniformly distributed disk instead of a point.

The point spread function (PSF) of the degraded image caused by defocus is:

$$h(x,y) = \begin{cases} \frac{1}{\pi R^2}, & x^2 + y^2 \le R^2 \\ 0, & otherwise \end{cases}$$

The degradation process can be expressed as:

$$g(x,y) = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} f(\alpha,\beta)h(x-\alpha, y-\beta)d\alpha d\beta + n(x,y)$$
$$g(x,y) = f(x,y) \otimes h(x,y) + n(x,y)$$

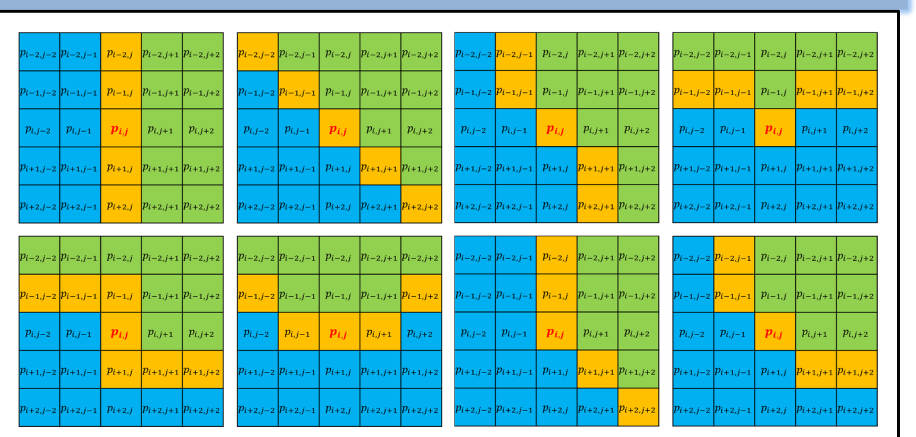
Noise Reduction

Purpose

An impulse noise filter based on image segmentation and region growing (ISRGF) has been proposed for removing high level of impulse noises.

Image Edge Detection

A variety of image edge patterns were defined for accurate image edge detection. The corrupted pixels are replaced temporarily according to the results of image edge detection.



Eight typical image edge patterns

Noise Reduction

Image Segmentation

1. Scan the image output from the Canny edge detector, mark the first unmarked pixel (x_0, y_0) at image edges with a new number;
2. If the pixel (x, y) in the eight-neighbor of (x_0, y_0) is located on the image edges, mark it with the same number with (x_0, y_0), and push it into a stack;
3. Extract a pixel from the stack, and take it as (x_0, y_0), then return to step 2);
4. Return to step 1) when the stack is empty;
5. Terminate the procedure until all pixels at image edges are marked.

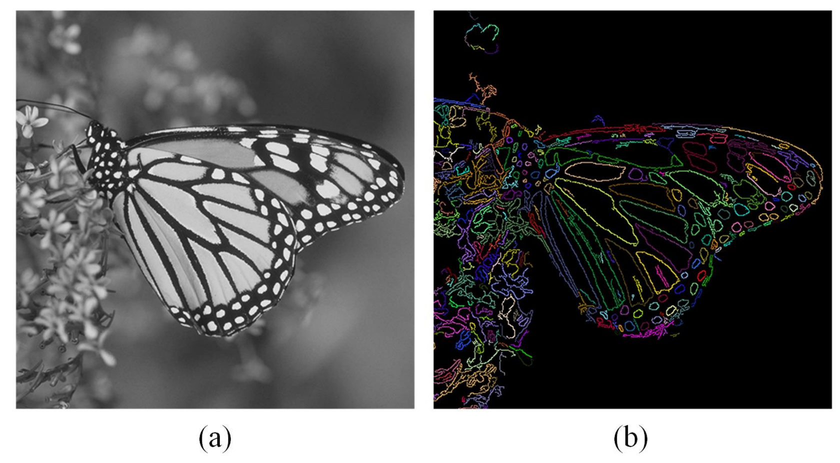


Image segmentation and image edge linking

The adjacent pixels at image edges with similar grey values share the same color, while different image edges are assigned different colors. So that the original image is segmented into many irregular regions by image edges.

Region Growing

It is Obvious that pixels in the same region have similar gray values. Therefore, the corrupted pixel is replaced by the average value of the irregular region which contained the corrupted pixel.

(a)

124	124	116	0	118	113	114	255
164	0	255	156	255	120	0	116
188	196	188	255	156	255	148	116
188	196	196	188	0	188	162	255
196	188	0	188	188	188	0	188
172	255	188	0	255	188	188	196
158	156	188	158	152	160	0	255
122	255	152	255	122	126	0	255

(b)

132	140	255	172	0	255	0	255
132	255	164	194	0	164	0	190
132	140	172	0	255	192	0	255
140	140	255	0	172	192	194	190
132	0	74	72	0	164	255	255
130	255	164	255	64	72	162	255
138	255	166	255	64	64	72	0
0	138	255	64	0	64	70	74

(c)

120	0	144	0	142	140	140	255
0	255	148	120	116	255	255	146
0	76	255	255	0	116	0	118
92	118	88	0	116	255	0	146
255	84	0	80	118	140	142	142
84	114	0	114	255	0	144	138
116	0	62	255	60	44	120	114
60	255	0	76	0	255	0	58

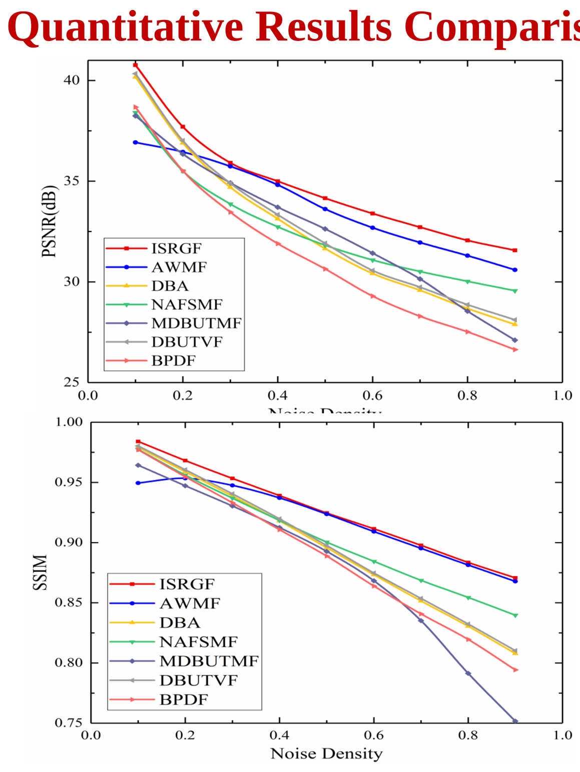
The results of region growing for (a) corrupted pixel in the texture, (b) corrupted pixel at the image edge, (c) isolated corrupted pixel

Weighted mean filter

$$p_{i,j}^{corrupted} = \frac{\sum_{p_{x,y} \in M_{i,j}} w_{x,y} p_{x,y}}{\sum_{p_{x,y} \in M_{i,j}} w_{x,y}}$$

$$w_{x,y} = \frac{1}{d_{x,y}^n}$$

Quantitative Results Comparison



Restoration results in PSNR and SSIM

Image Deblurring

Estimation methods for defocus radius include:

- Bessel function analytical method;
- Error-parameter analysis method;
- Laplace operator-based estimation method.

There is a sharp peak in the surface of self-correlation S, which is surrounded by an annular groove. The theoretical value of the radius of the annular groove is the defocus radius.

$$\nabla^2 g(x,y) = f(x,y) \otimes \nabla^2 h(x,y)$$
$$S = \nabla^2 g(x,y) \bowtie \nabla^2 g(x,y) = (f(x,y) \bowtie f(x,y)) * (\nabla^2 h(x,y) \bowtie \nabla^2 h(x,y))$$

Lucy-Richardson algorithm

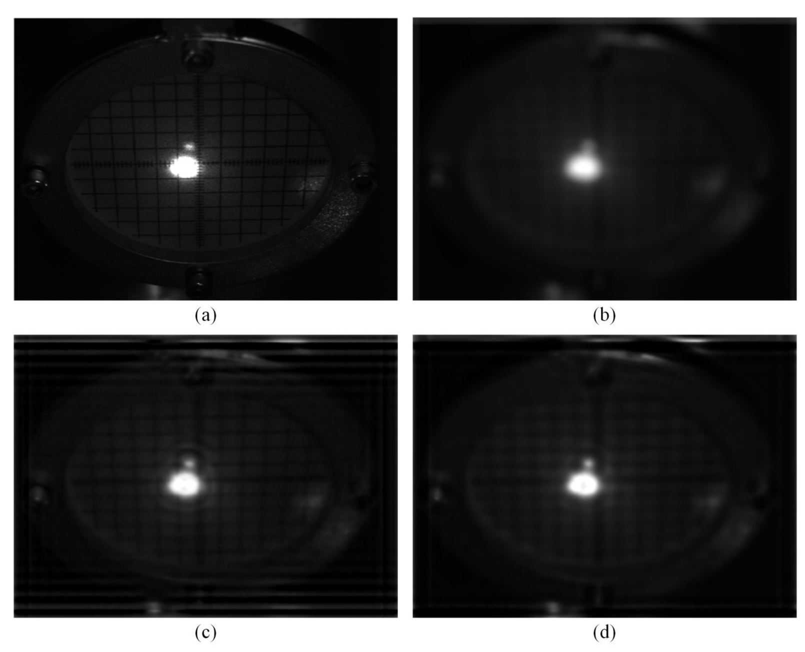
The basic idea of Lucy-Richardson algorithm is to approximate the maximum likelihood estimation of the original image through iterative calculation.

$$f(x,y)^{n+1} = f(x,y)^n \left[\left(\frac{g(x,y)}{h(x,y) \otimes f(x,y)^n}\right) \bowtie h(x,y)\right]$$

Wiener Filter

The principle of Wiener filter is to find an optimal restored image to minimize the mean square error with the original image.

$$F(u,v) = \left[\frac{1}{H(u,v)} \cdot \frac{|H(u,v)|^2}{|H(u,v)|^2 + \left[\frac{S_{nn}(u,v)}{S_{ff}(u,v)}\right]}\right] G(u,v)$$



The comparison of the performance of the Wiener and Lucy-Richardson algorithm

Conclusions

To improve the precision and efficiency of beam profile measurement system, a calibration method has been conducted for the calibration of the imaging system. Moreover, a new image noise reduction algorithm and two image restoration algorithms have been developed to restore images. The experiment results show that the calibration procedure and image restoration algorithms greatly improve the measurement accuracy of beam profile parameters, which enable the system to provide quantitative information for beam diagnosis.