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ANALYSIS OF CENTROIDING ALGORITHMS FOR NON-DIFFRACTING BEAMS

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ABSTRACT

This work explores the potential of optical-based systems, specifically pseudo-non-diffractive beams, as an alternative for alignment. The study focuses on Structured Laser Beam and Hollow Structured Laser Beam, which exhibit lower divergence and enhanced detection capabilities. The research objective is to analyze and compare centroiding algorithms for SLB and HSLB in terms of accuracy and robustness to noise. The study compares the Gamma Center of Gravity, Correlation Template Matching, and Thresholding Center of Gravity. It also introduces a novel Polarization based algorithm.

INTRODUCTION

A multi-point alignment of particle accelerator components is a challenging task due to the need for accuracy in tens of micrometers over hundreds of meters. The fundamental approach of these systems involves measuring the offset relative to a reference line. At CERN, the European Organization for Nuclear Research, line reference systems such as a Wire Positioning System combined with a Hydrostatic Leveling System were developed to meet tight accuracy needs [1]. While these systems exhibit high precision, they also have limitations such as implementation complexities and component costs.

Using an optical-based system as a reference line serves as a potential alternative. Several optical-based systems for the alignment of structures over long distances have been presented in various works [2, 3]. One drawback of these systems is a relatively high divergence of optical systems caused by diffraction, which makes the straight-line reference measurement more challenging over long distance.

A Structured Laser Beam (SLB) and Hollow Structured Laser Beam (HSLB) are pseudo-non-diffractive beams with lower divergence of the central core compared to diffraction limited systems. This work provides a quantitative in-depth analysis of algorithms, Thresholding Center of Gravity (TCoG), Gamma Center of Gravity (GCoG), Correlation Template Matching (CORR) and Polarization based algorithm (POL). They can be used for the detection of the BB, SLB, or HSLB centroid. This knowledge gap is critical for quantifying the error introduced by the algorithm in the alignment system.

CONCLUSION

These results indicate the potential of a SLB and a HSLB for long-distance accelerator alignment, where the required accuracy is typically in the units or tens of micrometers. It also suggests that centroiding algorithms will not be the primary or decisive source of error.

METHODOLOGY

The data used for the analysis were generated through numerical simulations utilizing custom-developed software. The simulation process involved tracing rays through the SLB generator. The input field of the SLB was linearly polarized, while for the HSLB, it was radially polarized. For long-distance applications, where the beam can travel over hundreds of meters, it is necessary to detect the centroid position at multiple points, each at a different distance. Hence, it is crucial to evaluate the performance of the algorithms for beams with various core sizes due to divergence. To generate intensity distributions in different distances, a numerical calculation of a Fresnel diffraction integral was performed for the traced field directly behind the generator and propagated to distances from 2 m to 102 m with a step size of 2 m. This resulted in 51 intensity distributions that were subjected to subsequent analysis. The virtual camera chip had dimensions of 10x10 mm, with 2001x2001 pixels (px).

A rectangular region of interest (ROI) measuring 1501x1501 px was extracted from each simulated intensity distribution. The corresponding position of the centroid for both the ROI and the beam was established. Subsequently, a sub-pixel shift of 0.31 px was introduced in both axes for the ROI centroid using bicubic interpolation to relatively displace the beam and ROI centroid. This means that the position of the beam centroid never was exactly in the middle of the pixel, hence the symmetry did not affect the result. This accounted for real measurement conditions. Consequently, the centroid coordinates for both axes were adjusted to 751.31 px. Shifting the beam to different positions within the ROI was tested without affecting the overall results.

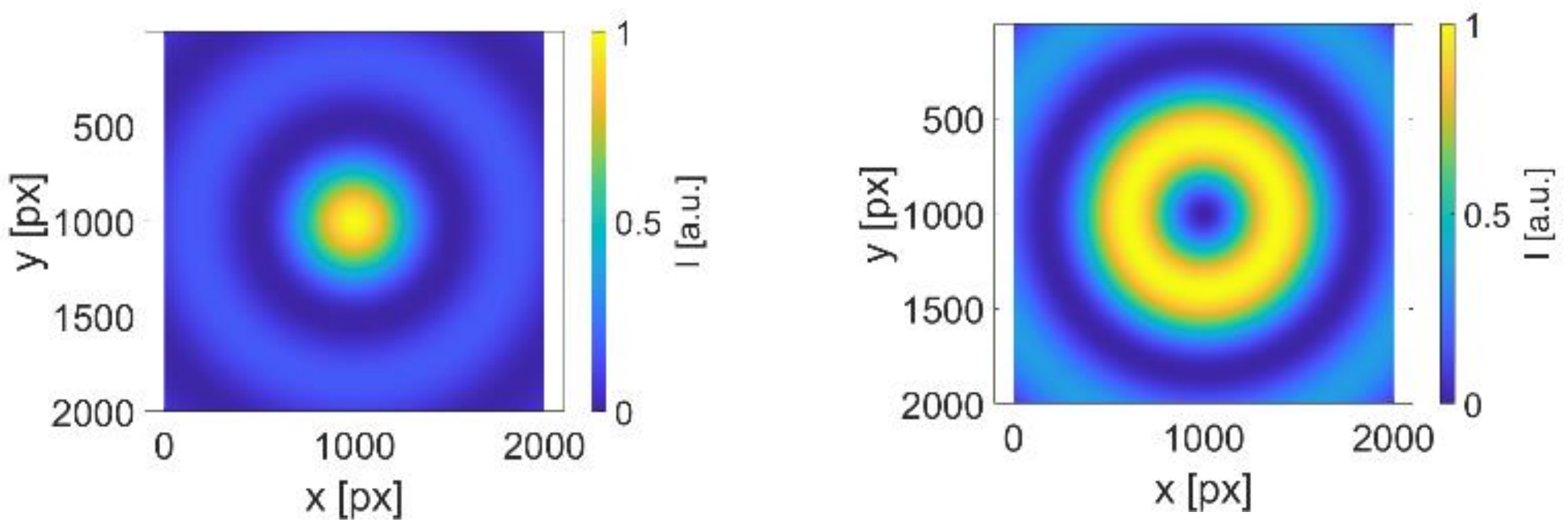

Fig. 1: SLB and HSLB intensity profiles

RESULTS

The results indicate that the GCoG algorithm is the least affected by algorithm parameter choice and exhibits the highest overall accuracy for SLB. It also demonstrates robustness to noise influence. . However, for HSLB, the GCoG algorithm is more sensitive to the choice of the parameter. For SLB, the CORR algorithm shows comparable accuracy to GCoG for core sizes larger than 500 px but performs significantly worse for small core sizes. Additionally, the CORR algorithm consistently exhibits robustness to the choice of algorithm parameters for both beams. In comparison, the TCoG algorithm performs with lower accuracy than the GCoG and CORR for both beams and is also sensitive to the choice of the parameter.

The POL algorithm is the most sensitive to noise and yields the lowest accuracy among the algorithms, particularly for small core sizes. The CoG-based algorithms are considerably faster than CORR and POL, especially when working with high- resolution images. However, the speed of CORR and POL can be increased through windowing without compromising algorithm accuracy. The speed of the CORR algorithm can be enhanced to match the level of CoG-based algorithms.

Overall, the centroid detection algorithms induce smaller errors, approximately one order of magnitude smaller for the SLB compared to the HSLB, when considering noise. The induced error for SLB ranges around 1e-2 px for most algorithms and noise values, while for the HSLB, it is in the order of 1e-1 px.

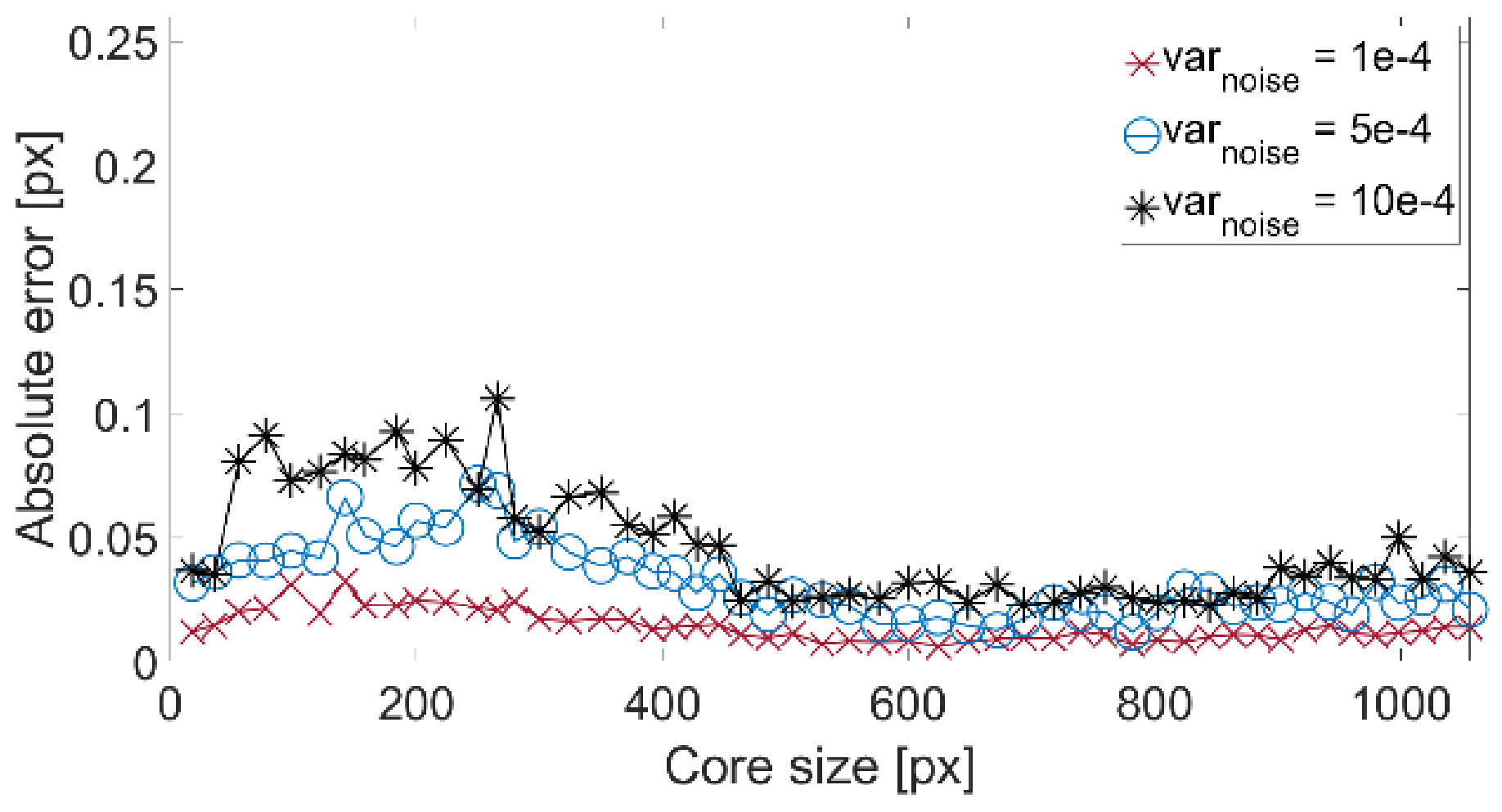

Fig. 2: Absolute error for different core sizes for CORR algorithm for different values of Gaussian noise variance

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