Images Processing Techniques and Data Analysis Applied to High-Power Laser Systems

Bertrand de Boisdeffre, Mihai Caragea, Ioan Dancus, Daniel Ursescu
ELI-NP project, Laser department
Horia Hulubei National Institute for Physics and Nuclear Engineering
Magurele, Romania
e-mail: bertrand.boisdeffre@eli-np.ro, mihai.caragea@nipne.ro, ioan,dancus@eli-np.ro, daniel.ursescu@eli-np.ro

***Abstract* — Extreme-Light Nuclear Physics (ELI-NP) facility in Romania is part of the pan-European distributed facility that addresses laser physics research with emphasis in the field of nuclear physics (in Romania), secondary radiation sources (in the Czech Republic) and attosecond light science (in Hungary). At ELI-NP, experiments will be carried out by using a High-Power Laser System (HPLS) delivered by Thales Company. Within the HPLS, cameras acquire images at different frequencies (from 10 frames per second to 1 frame per minute). They contribute to more than 90% of the data produced each day (around 700 gigabytes). These data are stored in Hierarchical Data Format 5 (HDF5) files on different servers located in the HPLS network. Thus, in this paper, we aim at presenting how digital image processing techniques applied on images can be used to reduce the amount of data that should be stored at the ELI-NP data center. The ensemble of these techniques were grouped and structured in order to form a laser beam detection algorithm. The algorithm was tested on different laser beam intensity profiles (Near-Field and Far-Field). As a conclusion, this paper offers a perspective upon the future development of testing quantitatively the algorithm and improving it.**

Keywords-laser; image processing; HDF5; data analysis.

I. INTRODUCTION

Research in the field of laser physics has been growing for the last thirty years especially after the development of the chirped pulse amplification technique [1]. The latter was recognized as one of the most important scientific achievements being awarded the Nobel Prize in Physics in 2018. In 2006, the European Strategy Forum on Research Infrastructures decided to build a pan-European distributed research facility, the Extreme Light Infrastructure (ELI) [2]. The implementation phase is on-going in three countries (the Czech Republic, Hungary and Romania). If the three pillars aim to host different but complementary experiments, all of them are making use of High-Power Laser Systems (HPLS). Such a system is currently being implemented in Romania by Thales.

The HPLS at ELI-NP is partially functional and the data acquired through its complex Distributed Control System (DCS) are already available. The DCS contains more than one hundred laser diagnostics instruments. Complementary metal–oxide–semiconductor (CMOS) cameras are the key instruments when considering the volume of data produced. Some of these cameras are not triggered externally, resulting in the acquisition of images without any laser beams. Our main goal is to eliminate data (images) without valuable information by implementing a laser beam detection algorithm. To our knowledge, this problem was not addressed in other laser facilities. Most of the time, the methods found in the literature aim to perform alignment tasks [3][4] and are based on alignment loop using weighting centroid and pointing algorithms [5]. Specific needs, such as laser beam classifications, led to the development of other techniques based on convolutional neural network, as presented in [6].

Our approach is quite different because we cannot assume that the image contains a beam a priori. Additionally, the dataset we have to process is large and diverse because the images come from different laser subsystems and may capture different profile intensity measurements (e.g., Near-Field and Far-Field). Our algorithm is primarily relying on region-based segmentation [7] and is similar to the autofocus algorithm presented by Gu [8]. If the first part of the two algorithms (filtering and segmentation techniques) is the same, the last part is not. We consider indeed that the laser beam cannot always be modelled as a circle or an ellipse. This assumption was made after we conducted a visual analysis of the laser beam images already available from the HPLS, in particular when looking at Far-Field beam intensity profiles. Instead, we propose to use a convex-hull algorithm [9] that was tested on few images samples.

The structure of the paper is the following: in Section II, we present the structure of the data that had to be processed. Section III describes how a laser beam detection algorithm has been developed by using threshold segmentation techniques combined with non-linear filtering and convex hull algorithm. The paper concludes with the work to be carried out in the future in order to improve the current algorithm.

II. DATA STRUCTURE

The data stored by the HPLS DCS are using a specific Hierarchical Data Format, HDF5 [10]. The HDF5 format is based on an Abstract Data Model relying on three key concepts: File, Group, and Dataset. They are presented in Figure 1.

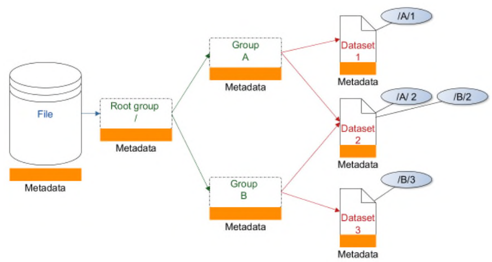


Figure 1. Simplified view of the HDF5 structure

The File is a storage container for organizing objects of mainly two types: Groups and Datasets. A Group is similar to a filesystem directory and contains Groups or Datasets linked together with parent-child relationships. Finally, the dataset is a multidimensional array of data elements. Each dataset relies on diverse properties that characterize it. All the images to be analyzed by the algorithm presented in the next section are stored in such HDF5 files.

III. Laser Beam Detection Algorithm

The laser beam detection algorithm is divided into four main steps:

1) Access to input data and creation of python numpy array
2) Segmentation with a threshold algorithm
3) Noise filtering with a median filter
4) Beam detection with the convex hull algorithm

A. Access to input data and creation of numpy array

The access to the data is made by opening the HDF5 file with the use of the h5.py python modules. The matrix of pixels contained in the HDF5 file is stored as a numpy array. This array is used as an input for the algorithm. Numpy array was selected because it uses less memory than classical python lists [11] and a vast number of python packages for image processing were developed around it [12][13].

B. Selection of a threshold algorithm

To isolate a specific object/region in an image, several segmentation techniques exist. In this study, we focused on two threshold techniques: minimum-threshold algorithm and Otsu threshold algorithm [14].

1) Minimum threshold algorithm

The algorithm can be explained by the formula below:

$$g(x,y) = f(x,y), \quad \text{if } f(x,y) \geq T$$
$$g(x,y) = 0, \quad \text{if } f(x,y) < T$$

- *f(x,y): value of the pixel located at the (x,y) coordinates in the original image*
- *T: threshold value*
- *g(x,y): value of the pixel located at the (x,y) coordinates after processing*

Usually, the laser beams are modeled with Gaussian, or Super-Gaussian distributions [15]. When considering Gaussian beams, the maximum intensity is located at the center of the beam. The diameter can be measured either at "Full-Width-Half-Maximum" (FWHM), either at "$1/e^2$". In the first measurement, the optical intensity drops to ½ of the maximum intensity value. In the second case, the optical density drops to 13.5% ($1/e^2$) of the maximum intensity. These beam diameters measurements are represented in Figure 2.

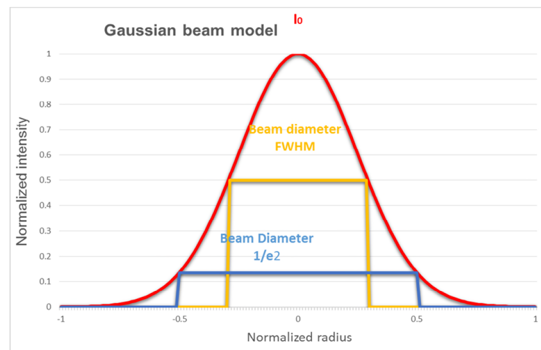


Figure 2. Intensity of a Gaussian beam with the representations of the beam diameters at FWHM and $1/e^2$

Based on these measurements, we defined two threshold values:

- $T_1 = I(FWHM) = I_0/2$
- $T_2 = I(1/e^2) = I_0 * 1/e^2$

I_0: peak intensity of a Gaussian beam

After empiric tests, it appears that the threshold value T_2 is better - the shape of the original beam is preserved - than T_1 (see Figure 3).

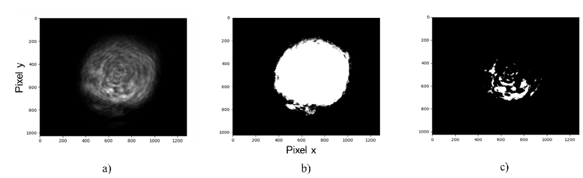


Figure 3. a) Original image; b) image processed with the "$1/e^2$" threshold; c) image processed with "FWHM" threshold

2) Otsu threshold algorithm

This threshold algorithm is named after its inventor (Nobuyuki Otsu). The algorithm is quite complex, but the main idea can be expressed as follows: the algorithm calculates automatically the optimized threshold value to be applied on an image. This calculus is based on the histogram of the image. Nevertheless, the algorithm "assumes" a bimodal distribution of the histogram (the image should be divided between background and foreground pixels).

Additionally, the algorithm needs a sharp valley between the two peaks of the histogram and cannot work if the background and foreground pixels are too different in terms of size (e.g., a small object in comparison with its background). To implement the Otsu algorithm, the scikit-image module was used. “Near-Field” and “Far-Field” beam profile images were processed with this technique (see Figure 4). The threshold values computed for the images are available in the Table 1.

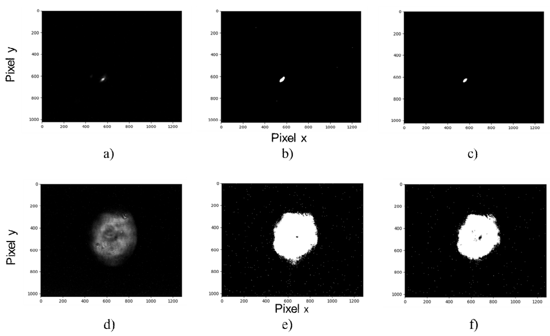


Figure 4. Left column, original images; middle-column, images processed with “1/e^2 threshold; right column, images processed with Otsu threshold

TABLE I. EXAMPLE OF THRESHOLD VALUES DEPENDING ON THE THRESHOLD ALGORITHM

Image	Type of image	1/e^2 threshold value	Otsu threshold value
a)	Far-Field	470	948
b)	Near-Field	214	296

The Otsu threshold tends to eliminate more information than the minimum threshold “1/e^2” (due to a higher threshold value). This is acceptable for “Near-Field” beam profiles but becomes more problematic for the “Far-Field” beam profiles.

As a conclusion, the images are segmented in two regions: beam (“white region”) and background (“black region”). To identify the surface of the “white region”, the convex hull algorithm is used, however not without a pre-filtering, as we will observe in the next paragraph.

C. Median filtering

The application of threshold methods has a drawback. When a “noise” is present on the original image, both threshold techniques tend to amplify it and produce a “salt” noise (see Figure 5). To eliminate this noise, a median filter [16] is used after the thresholding process. The size of the median filter windows has an influence on the “white segmented region”. The median filter tends to smooth the region and the bigger the window is, the smaller the “white region” becomes. Different sizes were tested: from 3 to 15. After the filtering process, the image is segmented in two regions. In an ideal scenario, the white region (laser beam) is either circular, either slightly elliptic and could be easily characterized by its smaller inner/outer circle/ellipse. The reality is quite different because laser beams can have “non-canonic” geometrical forms (see image a) in Figure 4), “critical points” that we define as points located in the white region but having a zero value (see Figure 5).

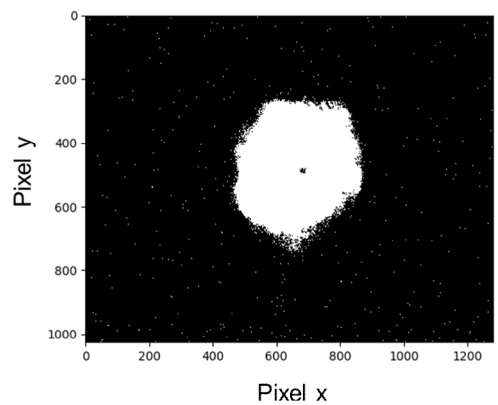


Figure 5. Example of image with a salt noise obtained after threshold algorithm processing

D. Convex hull algorithm and preliminary results

To overcome the issues previously mentioned, we propose to find the smallest convex set that will contain all the points of the “white region”. In other words, the set will represent the smallest convex polygon containing all the points of the “white region”. The advantage of this technique is that the polygon will be much closer to the form of the laser beam than the classical inner/outer circle/ellipse/rectangle, etc., but only if the image was correctly segmented and filtered before. Figure 6 shows the problematics encountered when applying this algorithm.

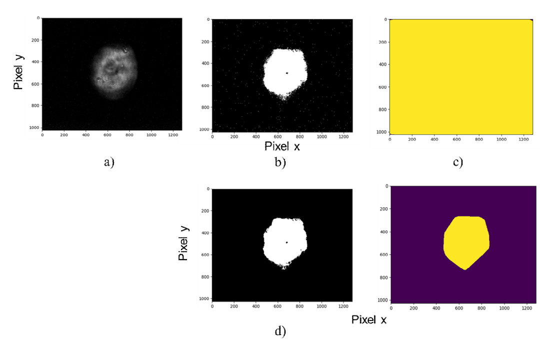
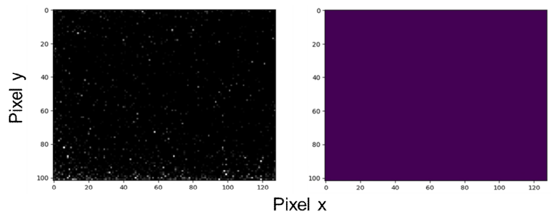


Figure 6. a) Original image; b) & d) segmented image w/out & w/ median filtering; c) & e) results of the convex hull algorithm

In Figure 6, the polygon containing the white region is filled in yellow. In picture c), the polygon covers almost the entire image due to the noise that was not filtered. In picture e), the polygon shape is close to the original beam shape. Once the polygon is determined, its properties (centroid, perimeter, surface, etc.) can be measured. The resulted properties can be used to characterize the laser beam. Finally, the laser beam detection algorithm was tested on an empty image. The result is presented in Figure 7.



a) b)

Figure 7. a) Original image; b) result of the beam detection algorithm

The image b) In Figure 7 does not contain any polygon, which is equivalent to the fact that no beam was detected.

IV. CONCLUSIONS

The results obtained with the laser beam detection algorithm are encouraging, but are based on a few image samples. This is the reason why quantitative methods for measuring the information lost during the processing will be tested in the near future. We envisage using the following region-based metrics: Overall Pixel accuracy and Jaccard Index. Additionally, future work will be necessary to implement a real-time algorithm. At this moment, the algorithm is an offline processing made at the ELI-NP data center in order to sort images with beam and images without beam. With a real-time algorithm running directly on the server acquiring images, it would be possible to store only valuable data in the ELI-NP datacenter.

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