Robust Beam Width Estimation with Sub-Pixel Resolution in Uncontrolled Imaging Conditions

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Abstract

Estimating the laser beam widths from a single image of numerous laser beams, which have a spatial extent of only a few pixels on the sensor, is not straightforward. Various beam width estimation methods are described in literature but the presence of image noise or background signals can heavily distort their estimated beam width. In this paper, we examine the feasibility of an image analysis method, proposed in the field of laser eye safety, to determine a laser's beam width. Here, the estimated beam width corresponds to the size of the evaluation window for which the ratio, referred to as the MTH ratio, between the beam power encircled by the evaluation window and its diameter is maximal. Based on simulations and experimental data, we show that this method yields accurate beam width estimations for different transverse beam profiles. We also demonstrate that the method is robust to noisy imaging conditions or the presence of background illumination. Moreover, we expand this method to make precise and accurate sub-pixel resolution beam width estimations on an image of multiple beams which are only of a few pixels large each.

Introduction

Laser beam profiling is the process to measure and quantify the (transverse) irradiance profile of a laser source. Commonly, laser beam profiling techniques use a CCD or CMOS sensor to obtain a 2D image of the irradiance profile where the grey value of each pixel represents the local irradiance of the laser beam incident on the sensor [1]. The most critical property examined through beam profiling is the laser's beam width. Common beam width estimation methods are the D4σ or second order moment method corresponding to the ISO 11146 standard [2], the D86 method [3], and the knife-edge method [4]. However, these methods are sensitive to noise or background offset levels on the measurement data [1]. Since in an industrial setting the imaging conditions are typically not precisely controlled, the need for a laser beam width method that works well under poor imaging conditions arises. Additionally, it might be of interest to have a method which can estimate the beam widths of multiple laser beams from a single image while the laser beams have a spatial extent of only a few pixels on the sensor. For these purposes, we investigate the usefulness of the so-called maximal thermal hazard (MTH) method introduced by Schulmeister et al. (2006) in [5].

Robustness of the MTH Method in Uncontrolled Imaging Conditions

In the MTH method, one searches for the most hazardous combination of power within an area of the irradiance profile and the diameter of that area. The MTH beam width is defined as the diameter of an evaluation window for which the ratio of the power within the window's area and the diameter of the window is maximal [5].

Let us consider circular top-hat irradiance profiles. A top-hat laser beam is defined by an irradiance profile $I(x, y)$ which has a constant amplitude I_o within the profile's diameter.

A typical graph of the MTH method, employing a varying circular evaluation window, applied to a computer generated top-hat irradiance profile with a diameter of 100 pixels is shown in Fig. 1. In this figure, we plot the ratio of the power within the circular evaluation window and the diameter of that evaluation window, henceforth referred to as the MTH ratio, as a function of the diameter of the evaluation window. If the diameter of the evaluation window is smaller than the spatial extent of the irradiance profile, the MTH ratio increases with increasing size of the evaluation window. When the evaluation window becomes larger than the irradiance profile, the MTH ratio will decrease as the power in the evaluation window will no longer increase. The evaluation window diameter for which the MTH ratio is maximal, is regarded as the profile’s beam width.

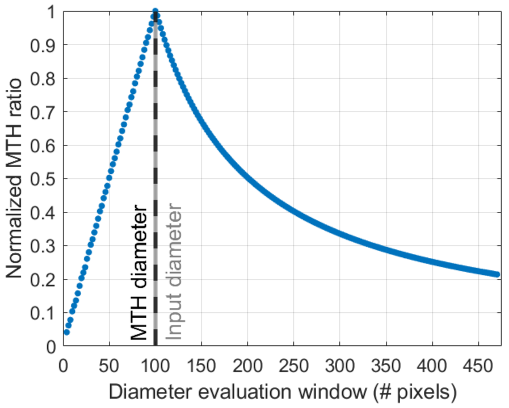

Fig. 1: Estimating the beam width of a circular top-hat irradiance profile as the diameter of a circular evaluation window for which the MTH ratio is maximal, indicated by the black dashed line. The input beam diameter of the top-hat irradiance profile is displayed by the grey line.

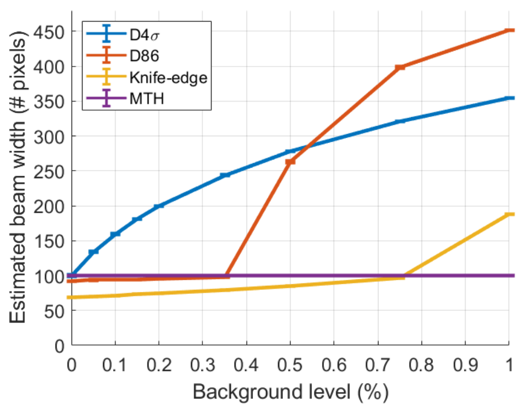

Fig. 2: The estimated beam diameters for all considered beam width methods in function of the added background offset level for computer generated top-hat irradiance profiles with a beam diameter of 100 pixels and with Poisson-Gaussian noise applied.

In order to assess the quality of the beam width estimation using the MTH method, we will compare its performance to the common beam width methods on images of computer generated top-hat irradiance profiles with varying strengths of background offset levels. The strength of the added background level is expressed as a percentage. For example, applying a background offset level of 1% on an image, the background offset level equals to 1% of the maximal pixel grey value of the image. For simplicity, a uniform background offset level across the entire image is considered and ranges from 0 to 1% in our simulation. Lastly, realistic image noise is added to the computer generated images using a Poisson-Gaussian noise model [6]. As the image noise will impact the results, we regenerate the noisy images and repeat the beam width estimations 100 times. The results on a top-hat irradiance profile with a beam diameter of 100 pixels are shown in Fig. 2 where we plot the mean value and the standard deviation of the estimated beam diameters in function of the applied background offset level. We observe that the D4σ, D86 and knife-edge beam width methods are highly susceptible to the presence of a background offset level in the image. Both the D86 and knife-edge method have a tipping point, i.e. a background offset level from which their estimated beam widths suddenly become extremely inaccurate. For the D86 method this tipping point is observed at a background offset level of about 0.35% and for the knife-edge method at about 0.75%. In contrast, the MTH method yields consistently accurate beam diameter estimations for each studied background offset level. In [7] we demonstrated the improved performance of the MTH method in more detail, e.g. also using experimental data of Vertical-Cavity Surface-Emitting Lasers.

Sub-Pixel Resolution Beam Width Estimations

A drawback of camera based beam profiling techniques is the limited resolution when the spatial extent of an irradiance profile on the sensor is small compared to the pixel size of the sensor. Therefore, it is generally recommended to fill the sensor's active area as much as possible with a single laser beam [1]. In this section, we will demonstrate that the MTH method can open the path to determine beam widths with a sub-pixel resolution of multiple irradiance profiles which extend only a few pixels on a single image.

In order to increase the resolution of the MTH beam width estimation, we assign weights to the pixels of the irradiance profile corresponding to the amount of overlap between the evaluation window and the pixels. If a pixel is entirely enclosed by the evaluation window, the pixel's signal value is fully added to the enclosed power. We can state that the pixel has a weight 1. Contrarily, the pixels located at the border of the evaluation window are typically only partially enclosed. For large beam diameters as the example in Fig. 1 and 2, these pixels are either completely added or disregarded depending on the amount of overlap when calculating the enclosed power. Now, these edge pixels are given a weight between 0 and 1, depending on the overlap of the evaluation window with that pixel. This overlap is determined through numerical integration using a Monte-Carlo technique. To calculate the enclosed power of an irradiance profile, the signal values of all evaluated pixels are weighted before summing them.

This pixel weighted MTH method is investigated on small top-hat irradiance profiles which are also generated using the Monte-Carlo integration technique. An example of the MTH ratio with a sub-pixel resolution of 0.04 pixels on a computer generated top-hat irradiance profile with a diameter of 3.6 pixels is given in Fig. 3. A good agreement between the input beam diameter and the estimated sub-pixel beam width is observed, illustrated by the grey solid line and black dashed line, respectively. The deviation of the estimated beam width with respect to the input beam diameter can be attributed to the fact that the pixel weighting technique assume that the irradiance across the pixel is uniformly distributed. This is not the case for pixels with a partial overlap of the irradiance profile. Nevertheless, if one would have used the non-pixel weighted MTH method with the resolution of only a pixel, the beam width would have been firmly underestimated as depicted by the red dashed line.

The goal is to accurately estimate the beam widths of small top-hat irradiance profiles with arbitrary diameter. We study the performance of the MTH method on noise-free images without a background offset level as well as on images with a background offset level of 0.1% and with Poisson-Gaussian noise applied. We repeat the beam width estimations 100 times and calculate the mean value and the standard deviation. We assess the quality of the beam width estimation of the pixel weighted MTH method by comparing the results with the non-pixel weighted MTH method. The beam diameter of the top-hat irradiance profiles is varied from 2 to 11 pixels in steps of 0.2 pixels. The sub-pixel resolution of the pixel weighted MTH method is set at 0.05 pixels. The results are shown in Fig. 4. While the non-pixel weighted MTH method nicely obtains the input beam diameter for integer input radii, it also returns integer values for non-integer input radii. While an error of the beam width estimation of 1 pixel can be acceptable for very large beam diameters, it yields poor beam width estimations for beam profiles only extending a few pixels. Displayed in red in Fig. 4, the pixel weighted MTH method increases the accuracy of the beam width estimation and removes the step-like behavior. For input beam diameters larger than 3 pixels, the maximal deviation between the beam width and its estimation is improved from 1.6 to 0.6 pixels, illustrated by the dashed lines in the figure. When the background offset level and Poisson-Gaussian noise is present in the computer generated images, the pixel weighted MTH method maintains the improved accuracy with a high precision.

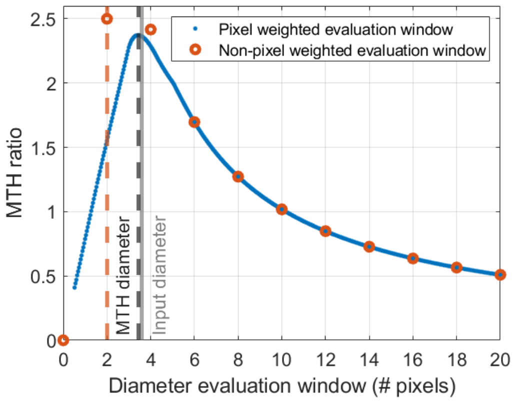

Fig. 3: The non-pixel weighted and pixel weighted MTH ratio of a top-hat irradiance profile with a diameter of 3.6 pixels.

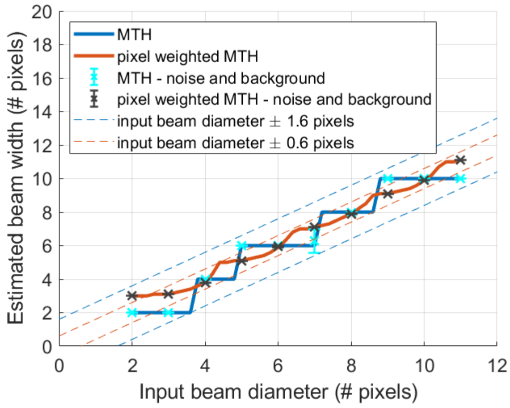

Fig. 4: The estimated beam widths for the pixel weighted and non-pixel weighted MTH method in function of the input beam diameter of computer generated top-hat irradiance profiles.

Conclusion and Future Perspectives

We have demonstrated that the MTH methods is a suitable beam width estimation method for circular top-hat irradiance profiles in poor imaging conditions. Compared to the commonly used beam width methods, the MTH method yields more precise and accurate results. Furthermore, we expanded upon the MTH method through a pixel weighting technique to estimate beam widths of only a few pixels large with a sub-pixel resolution without losing its robustness in poor imaging conditions.

The residual error on the sub-pixel resolution seen in Fig. 4 can be improved upon by handling the weighting of the edge pixels in a more advanced manner. Expanding the method to take into account the non-uniform irradiance distributions across the edge pixels, the pixel's signal value added to the enclosed power can be more representative.

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