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METHODOLOGY FOR RAPID MEASUREMENT AND COUNTING OF WATER MICRODROPLETS USING DIGITAL IMAGE PROCESSING

METODOLOGÍA DE RÁPIDA MEDICIÓN Y CONTEO DE MICROGOTAS DE AGUA USANDO PROCESAMIENTO DIGITAL DE IMÁGENES

PhD. Luis Gonzalo Vargas Q. [*], **MSc. Jose Pablo Montoya**[*],
Ing. Mario Alejandro Muñoz León[*], **Ing. David Alejandro Salazar P.** [*],
PhD. Alcides Montoya C. [*]

[*] **Universidad Nacional de Colombia,** Facultad de ciencias, Grupo de investigación en instrumentación científica e industrial.
Carrera 65 Nro. 59A - 110, Medellín, Antioquia, Colombia.
Tel.: [57 + 604] 430 95 75
E-mail: {gvargas, jpmontoyav, mamunozl, daasalazarpa, amontoya}@unal.edu.co

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Abstract: This paper synthesizes a procedure performed for counting and measuring the area and diameter of individual droplets generated by a piezoelectric fog generator. A camera-based optical array was constructed to capture images of the water droplets against backlight. Using ImageJ software, the Sauvola Auto-Local Thresholding technique was applied, simultaneously binarizing the focused droplets and discarding the out-of-focus ones. Subsequently, the area and diameter of the droplets were calculated and processed using MATLAB. The results show that the method performs adequately in both binarizing the focused droplets and discarding the out-of-focus droplets in a single step, which resulted in a reliable droplet count with a measurement accuracy of 5 micrometers.

Keywords: Digital Image Processing, Droplet Size Measurement, Spray Characterization

Resumen: Este artículo sintetiza un procedimiento realizado para el recuento y medición del área y diámetro de gotas individuales procedentes de un generador de niebla piezoeléctrico. Se construyó un conjunto óptico basado en una cámara para capturar imágenes de las gotas de agua a contraluz. Utilizando el software ImageJ, se aplicó la técnica de umbralización auto localizada Sauvola, binarizando simultáneamente las gotas enfocadas y descartando las desenfocadas. Posteriormente, se calculó el área y el diámetro de las gotas; datos que fueron procesaron usando MATLAB. Los resultados muestran que el método se comporta adecuadamente tanto en la binarización de las gotas enfocadas como en el descarte de las gotas desenfocadas en un solo paso, lo que resultó en un recuento fiable de gotas con una medición de 5 micrómetros de precisión.

Palabras clave: Procesamiento Digital de Imágenes, Medición de Tamaño de Gotas, Caracterización de Pulverizadores.

1. INTRODUCTION

Research into controlled environments and managed plant nutrition in greenhouses is gaining importance as worsening climate change forecasts point to scarcity of both water and fertile soil. Protected environment structures provide farmers with the possibility of growing a wide variety of crops in regions where they traditionally could not be grown. A particularly important factor in greenhouse plant growth is temperature, which can be controlled by limiting the ingress of infrared radiation through Mie scattering by water droplets with diameter values close to the wavelengths of the scattered radiation. However, this application requires measurement of droplet size for precise control (Wang et al., 2015).

Water droplets are most commonly measured through optical methods (Fritz & Hoffmann, 2016), as they offer a straightforward strategy to acquire the sizes and even their chemical composition without altering them in any way, allowing their characterization under normal operating conditions of sprinklers, sprayers, jet outlets and misting systems (Knop et al., 2021). The numerous setups used for optical measurement and counting of droplets can be broadly classified by the optical detection scheme used, either camera-based or photodetector-based as is the case for interferometric measurements. In this work we developed a camera-based approach due to its simplicity, relatively low cost and fast calibration procedure.

The methods commonly used for droplet imaging in agriculture are usually for sprinklers and pesticide delivery nozzles: Particle Image Velocimetry (PIV) (Gollin et al., 2017), laser Doppler interferometry/laser scattering [1], (Fritz & Hoffmann, 2016; Huber et al., 2016), fiber optic probes (Maaß et al., 2011), shadow imaging with ultra-fast camera (Hijazi, 2012; Damsohn & Prasser, 2011) and shadow imaging with stroboscope-illuminated camera (Minov et al., 2015). The latter was chosen due to its low cost and ease of implementation compared to the others.

For further image processing, different image analysis techniques were available, that allowed automatic droplet measurement, even in fog generators that produce high droplet density in small areas. These techniques included an Attentive Generative Adversarial Network (Li et al., 2020), convolutional neural networks (Soldati et al., 2018), deep learning approaches (Wang et al., 2018), and a remarkably interesting rainbow refractometry method (Shin & Lee, 2010; Porav et al., 2019; Wang et al., 2019) or a combination of these methods (Bissell et al., 2014). Other more traditional approaches included the use of the Hough transform for real-time droplet classification (Ramakrishnan et al., 2015) and gray level distribution statistics or other line-wise gray level profile analysis (Minov et al., 2015; Sudheer & Panda, 2000).

The final algorithm obtained was based on the steps for image optimization used in (Zhao et al., 2018) and (Chong et al., 2016), but instead of feature extraction, Sauvola autolocal thresholding (Sauvola & Pietikäinen, 2000) and binary blob analysis with imageJ/Fiji software were used.

2. EXPERIMENTATION

2.1 Experimental setup.

The setup consisted of a FLIR Flea 3.0 USB camera, a set of microscope lenses with a 140X zoom and a defocused diffuse backlight from a white LED as shown in Figure 1. This provided a uniform background and eliminated the need for strobe lighting as high-quality images of the droplets were obtained with the selected camera settings. The camera took backlit shadow images of the droplets at 60 FPS and a shutter time of 0.015 ms. Additionally, it took backlit shadow images of the droplets at 60 FPS and 0.016 ms shutter time. 600 frames were taken for each setup for a total of 10 seconds of droplet capture. Some of the results are presented in Figure 2. It can be seen how longer shutter time affects the apparent motion of the droplets, the focus of individual droplets, and the grey level depth. Other camera settings used include a gain of 24 dB and the use of automatic brightness correction. The droplets were produced from distilled water using a continuously operating porous piezoelectric fog generator.

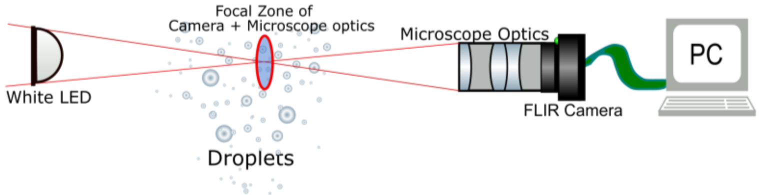


Fig. 1. Optical configuration, the focal zone has a measured width of 5 mm.

Fig. 2. Comparison of drop shadow images obtained from the same source with different shutter times: 1.6 ms (left), 0.16 ms (center), and 0.016 ms (right).

Prior to capturing images of the droplets, calibration of the system was performed by taking images of a C1 calibration ruler (1 mm long) with marks spaced 10 µm apart, before capturing each set of images. The distance between the marks was measured in pixels using Fiji/ImageJ software and a micrometer to pixel conversion factor was obtained from this. Since the microscope objective has a small focal depth of 3 mm, it was assumed that any droplet that is in focus can be measured in pixels and converted to micrometer units using the fixed pixel to micrometer ratio. In the calibration process, an equivalence of 4px (camera resolution) per calibration standard unit was identified, estimating the uncertainty of the optical system as 1px equivalent to 2.5 µm.

2.2 Análisis de imágenes.

The image analysis process was performed in Fiji/ImageJ software. Each shot was loaded into the software to apply three processes in order to identify the number of measurable drops per photo. The first droplet counting problem appears when their edge definition is not clear, in this case we have drops recorded by the camera that were not located in the focal plane range. For this reason, firstly, a background subtraction was performed for each of the shots, followed by contrast optimization. After this process there was some remaining noise. The solution consisted in applying a blur filter called Median Filter in ImageJ, as used in (Wu et al., 2004). Finally, Sauvola's automatic local thresholding technique was applied to binarize the drops and to be able to perform a reliable count. A set of sample images from each step is shown in Fig. 3.

After thresholding and binarization, Fiji/ImageJ allows the user to extract information about counting a set of white pixels that form an area (each of the droplets) and the information about that area. The characteristics of this area fit those of an ellipse, represented in Fig. 4. These parameters, all in pixel units, are its XY coordinates of the length of its major and minor axes and the angle between them along with the reference plane. The software provides a .csv file with all the information in the form of columns for each solid white droplet or "particle" found in the image.

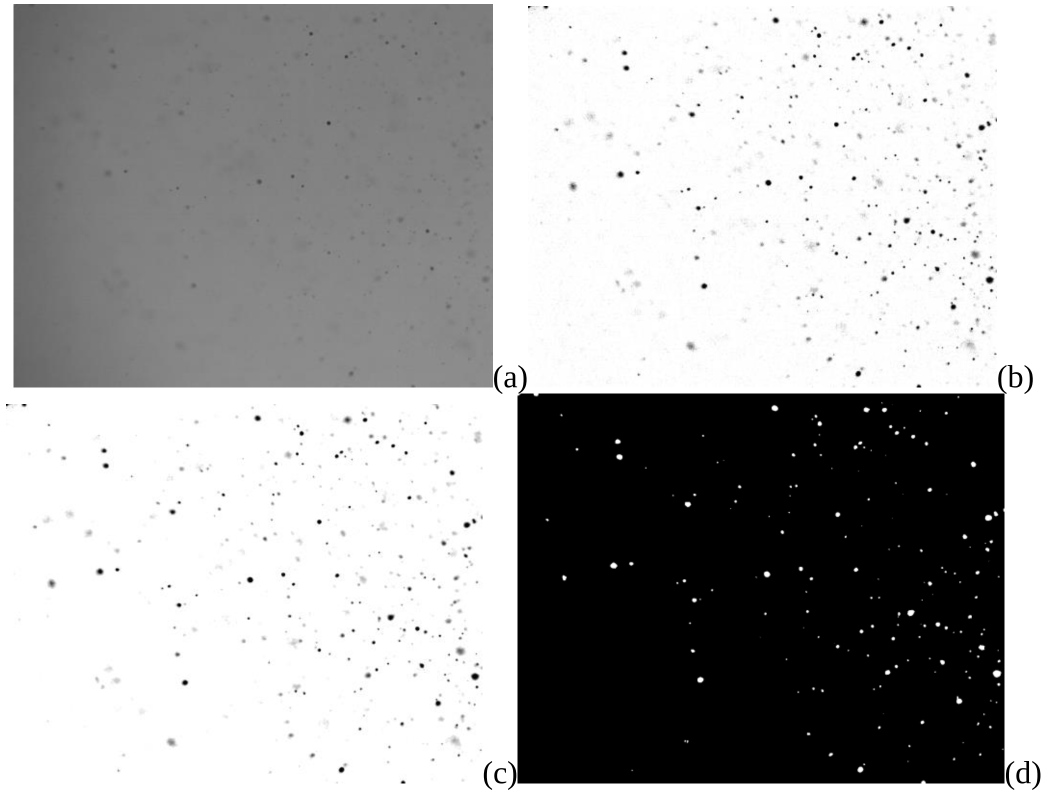


Fig. 3. Example of image preprocessing and application of Sauvola's automatic local thresholding. (a) real image, (b) image with background subtraction, (c) image with blur filter, (d) resulting image with Sauvola.

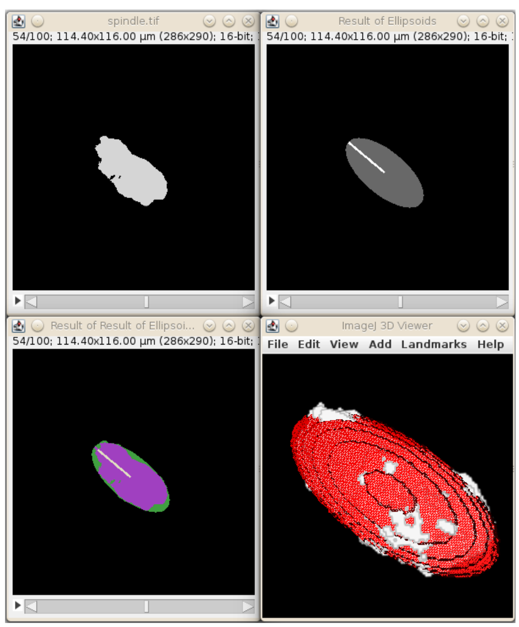
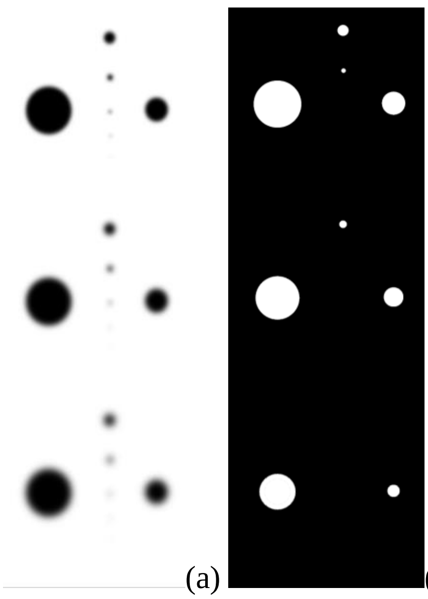


Fig. 4. Ellipse from the particle analysis function of ImageJ/Fiji software. Taken from: https://imagejdocu.tudor.lu/tutorial/plugins/3d_ellipsoid under CCBYSA3.0.

Since the initial idea of the article is to have an approximation of the drop size in each image, a comparison pattern must be had.

The performance of the method was tested on a reference image simulating different levels of drop blur by applying a Gaussian filter with incremental radius. In this case, it was an experimental pattern made from a reference image with six levels, each level with a BLUR Gaussian filter with radii of 0px (ground truth), 2.5px (perfect image possibly acquired by the camera), 5px (only the minimum viable circle is considered blurred), 10px, 15px and 20px (fully blurred). When the filter radius is larger than the drop diameter, the width of the drop cannot be accurately measured from its shadow image, so these drops must be discarded. Fig. 5 shows the lower half of the reference image together with its binarized version after applying Sauvola's automatic local thresholding. It can be observed that the circles with a higher degree of blur are excluded after applying the filter, thus simulating drops with a certain degree of blur.



(a) (b)

Fig. 5. (a) Lower half of the reference image used to test the method and (b) result of the Sauvola automatic local thresholding process.

After thresholding and binarization, Fiji/ImageJ allows the user to extract information about the count of a set of white pixels that form an area (each of the droplets) and the information about that area. The characteristics of this area fit those of an ellipse, represented in Fig. 4. These parameters, all in pixel units, are its XY coordinates of the length of its major and minor axes and the angle between them along with the reference plane. The software provides a .csv file with all the information in the form of columns for each solid white droplet or "particle" found in the image.

3. RESULTS AND DISCUSSION

3.1 Analysis of results

The processing of the data from the .csv file containing the results is performed in the Mathworks ® MATLAB software in a simple sequence of discarding non-viable drops, applying the calibration scale from pixels to micrometers and finally plotting histograms together with the mean values and standard deviation of the droplet diameter data.

The methodology for graphically presenting the processed data was performed with a comparative histogram of the automatic local thresholding droplet data set and a manual binary thresholding data set, counting the drops by their size. Both histograms along with their mean diameter value and standard deviation are shown in Figure 10.

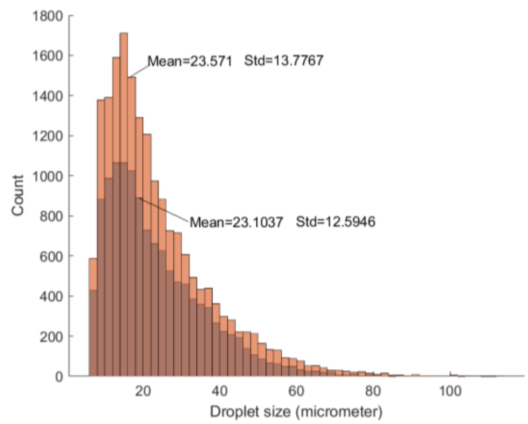


Fig. 6. Overlaid histograms of droplet size vs. count. Orange graph: Manual binary threshold, brown graph: Sauvola automatic threshold.

The graph shows that for both methods the highest number of droplets is between 10 and 30 µm in diameter, with a maximum peak around 15 µm. The manual binary threshold has a maximum count of approximately 1700 drops and the automatic binary threshold identified 1100 drops. The mean value of both data sets only varies by 0.467 µm. Comparing the standard deviation of the manual binary threshold count and the Sauvola automatic threshold count, it is found that the latter tends to be more clustered around its mean (Mean = 23.1037 µm, Standard deviation = 12.5946 µm), making it a data distribution that provides a more reliable diameter value for each drop and also improves the counting accuracy by limiting the counting of drops far from the focal area.

4. CONCLUSIONS

The methodology applied, both at the optical and computational level, is simple and affordable and allows obtaining significant results in a short time. The quality of the images and their capture technique is essential for the correct functioning of the image processing software and, therefore, to guarantee the reliability of the data obtained in post-processing. With our configuration we report measurements of fog droplets of size between 7.5 and 100 µm with an uncertainty of 2.5 µm.

Sauvola's automatic local thresholding filters out-of-focus droplets and binarizes the image in a single step, allowing to obtain an estimate of the number of droplets from a sequence of images that are located in the same plane. However, this does not work for droplets that are large relative to the observation area.

The technique described in this article can provide valuable first-hand information for the study of the physical characteristics of aerosols, atomized substances, fog generators and other cases involving particles with a size range of 10 -100 µm that may be of interest. Combining this system with coherent images or multispectral filtering can find applications for different branches of natural sciences such as medicine, biology and physics; as well as for the artistic field.

RECOGNITION

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