



Measuring the Size of Sugar Crystals in Suspension using Computer Vision and Deep Learning

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ABSTRACT/ RESUMEN

The measure of the dimensions of crystals from their digital images has received noticeable attention in the last years, given its importance in various application fields. In particular, for the case of sugar crystals in suspension, the method based in Image Processing is particularly valuable because the conventional sieving method used for measuring crystal dimensions in the sugar final product cannot be employed, and this was the motivation for the present work. Some authors have addressed this topic in the past two decades, in which there has been a noticeable progress in the Computer Vision (CV) field, both in conventional algorithms and in those based on Deep Learning with the use of Deep Convolutional Neural Networks (DCNN). This paper describes the development of a software tool capable of measuring the dimensions of crystals in suspension from digital photographs, by a combination of conventional CV and DCNN, specifically using for the latter the YOLO (You Only Look Once) model. The system is conceived to process a batch of digital images of crystals in suspension, detect and extract the individual crystals and calculate their dimensions (length, width, areas) and finally calculate and display some statistical measures associated to the analyzed set of crystals.

Keywords: Crystals Size, Sugar, Computer Vision.

La medición de las dimensiones de los cristales a partir de sus imágenes digitales ha recibido una atención notable en los últimos años, dada su importancia en diversos campos de aplicación. En particular, para el caso de los cristales de azúcar en suspensión, el método basado en el Procesamiento de Imágenes es especialmente valioso porque el método convencional de tamizado utilizado para medir las dimensiones de los cristales en el producto final de azúcar no puede emplearse, y esta fue la motivación del presente trabajo. Algunos autores han abordado este tema en las últimas dos décadas, en las que ha habido un progreso notable en el campo de la Visión por Computadora (VC), tanto en algoritmos convencionales como en aquellos basados en Aprendizaje Profundo con el uso de Redes Neuronales Convolucionales Profundas (RNCP). Este artículo describe el desarrollo de una herramienta de software capaz de medir las dimensiones de cristales en suspensión a partir de fotografías digitales, mediante una combinación de VC convencional y RNCP, utilizando específicamente para esta última el modelo YOLO (You Only Look Once). El sistema está concebido para procesar un lote de imágenes digitales de cristales en suspensión, detectar y extraer los cristales individuales y calcular sus dimensiones (longitud, anchura, áreas) y, finalmente, calcular y mostrar algunas medidas estadísticas asociadas al conjunto de cristales analizado.

Palabras claves: Dimensión de cristales, Azúcar, Visión por Computadora

Medición del tamaño de cristales de azúcar en suspensión mediante visión por computadora y aprendizaje profundo

1. -INTRODUCTION

1.1.- MEASURING THE SIZE OF CRYSTALS FROM MICROSCOPE IMAGES

In this section, the problem of measuring the size of crystals is presented and a group of papers published on this topic using different techniques have been reviewed. The process of crystallization is encountered in a number of industry and laboratory processes. With the development of Computer Vision (CV) and Image Deep Learning (DL) techniques, various tasks related to the process of crystallization in different fields have been performed using these tools, some examples of which are shown in different works analyzed in the following paragraph.

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The distribution of the sizes of crystals with different shapes is determined in [1] by means of image analysis and Deep-Learning, to be used in a feedback control system of crystal size distribution with a general shape. A system using a method of sparsity-based image analysis for monitoring crystal size distribution during crystallization processes is presented in [2]. Here the system includes the correction of various degradations present in such images, which are then used to determine the edges of the crystal shapes and reconstruct a denoised image in real time. Here the application to cooling crystallization of α -type L-glutamic acid (LGA) is presented to illustrate an effective application of the method. In [3] is proposed a high-speed imaging system to track the evolution of crystal population sizes in the process of cooling crystallization. In this work, U-net is used in order to detect appropriate crystals for the measurement from the acquired microscope images, then the crystal size distribution model is analyzed. Reference [4] presents a review that shows results obtained in modelling and simulation of crystal shape distribution, measurement and estimation of crystal facet growth kinetics, including 2D and 3D imaging for on-line characterization of crystal morphology and crystal shape distribution. An example of application in geology is presented in [5], where a review is presented in regard to the reproduction of crystal size distributions in rocks. Other references relevant to the analysis and measurements of crystals using Image Processing, Computer Vision and more recently Deep Learning, which are not commented here in more detail for space reasons, can be found in [6, 7].

In regard of measuring the size of sugar crystals, the techniques under study in this work have encountered an important application in the sugar industry, in which the research reported here pursues the development of a state of the art system, based in CV and Deep Convolutional Neural Networks (DCNNs), to measure the dimensions of crystal sizes in suspension, which appear in the massecuite during the production process. This situation precludes the use of sieving, a technique commonly applied for this purpose to the final product [8]. Considering the mentioned application to the Sugar Industry, various papers have been published since the beginnings of the 21st Century, a selection of which is commented in what follows.

An approach to the problem under study, based in the use of Deep Convolutional Neural Networks (DCNN), is presented in [9]. This work reports the development of a system to classify crystallization images from the sugar production process using DCNNs. To accomplish this, four different DCNN models were trained using an image data set obtained from a sugar crystallizer, and afterward the model obtained performed the task of classifying the sugar crystallization images into five categories. This paper declares that using the InceptionResNetV2 model, the obtained classification accuracy was between 0.83 and 0.99 when classifying the crystals, claiming that this was a promising method to develop future monitoring systems and that this model can serve as benchmark for future developments. Reference [10] starts recognizing as the main difficulty faced by the sugar crystals image processing systems, that the algorithms developed so far to accurately segment sugar crystals that touch or overlap are not enough efficient. The objective of the work reported in this paper was to create an appropriate image processing algorithm, capable of measuring the size and shape of crystals in sugar baking solution (massecuite), allowing to evaluate these parameters and influence positively the quality of the final product. The images acquired through a microscope with a digital camera were subjected to some operations (transform images to gray scale, morphological operations, noise filtering and others) using the MATLAB image processing toolbox, defining three methods to segment the image of crystals in massecuite. The accuracy of these methods was tested by comparison with a ground truth composed by images manually segmented using the ImageJ software [11]. After applying the segmentation algorithms to the reference image, seven geometrical parameters, like mean aperture (MA), coefficient of variation and standard deviation (SD) were calculated in the image for the sugar crystals present in it. The final step was the calculation of the percentage MA measurement error for all the sugar crystals, in order to find the best algorithm. As results, the three segmentation algorithms were tested by comparison of their results with a ground truth manually obtained and a combined method called Multiplicative Intrinsic Component Optimization (MICO)-Convexity was considered the best, with mean 13.4% error in mean value of a parameter related to the crystal size, called Mean Aperture. In the Conclusion section, the results obtained with this method are qualified as not much different to those obtained with the manual reference method.

1.2.- THE POINTS OF VIEW OF MODERN ARTIFICIAL INTELLIGENCE (AI) ON THE PROBLEM OF MEASUREMENT OF THE SIZE OF SUGAR CRYSTALS

This section analyzes the viewpoints and recommendations of two recognized AI systems and allows comparing these with the solutions proposed in this work. The information was obtained taking into account the interest in the present work, which is creating a practical crystal measuring software based in Python, considering the advantages of this language like being free software, as well as the many Image Processing, Computer Vision and Deep Learning tools that it possesses. The discussion is based in the answers to the question: “How to measure the sizes of small crystals in suspension by means of computer vision and Deep Learning using Python, from photographic images of the crystals taken using a microscope?” It is worth to

notice that although the IA also provides Python code, the main reason of including this requirement in the question was not to get that code, but to ensure that the programming resources used are available in this programming language.

The ideas provided by the IA systems in their answers to the formulated question cannot be considered as rigorous as the references cited in the scientific literature review, these were included here only to illustrate how IA pays attention currently to the problem addressed in this article.

1.2.1.-THE CHATGPT APPROACH

The related information can be found in [12], which was obtained by formulating the previously mentioned question to ChatGPT. The answer can be summarized in the block diagram shown in Figure 1.

Data preparation consists in acquiring a microscope images dataset and identifying the crystals by means of bounding boxes or masks. Then the images are annotated by means of an appropriate tool like LabelMe [13], in formats compatible with the Deep Learning framework used, and exported. The third block implies to select an appropriate DCNN model for the segmentation of crystals and train it with the image dataset previously prepared. Finally, in the fourth block, the model is used to process new images, extract the mask of crystals and perform the measures in pixels that are afterwards converted to physical units (e. g. micrometers) by means of an appropriate calibration. The answer included also an example in which, after detecting a crystal contour, its equivalent diameter is calculated assuming a circular shape.

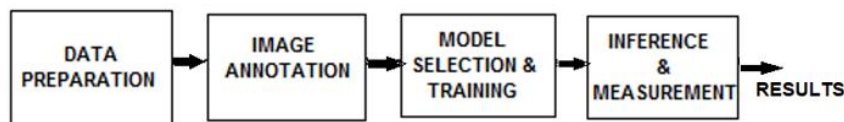


Figure 1

General crystal measurement process as proposed by ChatGPT.

1.2.2.-THE DEEPSEEK APPROACH

The related information can be found in [14], obtained by formulating the previous question to DeepSeek. The answer can be summarized in the block diagram shown in Figure 2.

In this case, as could be expected, there are similarities with the ChatGPT approach, but also differences. While ChatGPT proposes to select and train a DCNN model to detect, segment and measure the crystals, DeepSeek gives as alternatives to segmentation the use of traditional Computer Vision methods and on the other hand the use of Deep Learning (U-Net, Mask R-CNN) for these tasks. Then, the size measurements (length, width, area, etc.) are obtained analyzing the crystals contours. At the end, this approach suggests also the alternative of using a DCNN model like YOLO or Faster R-CNN to detect and measure the crystals. Here the calibration step to measure the crystals in physical units like microns is emphasized as a necessary step.

The present paper describes a work in which all the previously described experiences have been taken into account to develop a combined algorithm, which showed good results without requiring high computational resources.

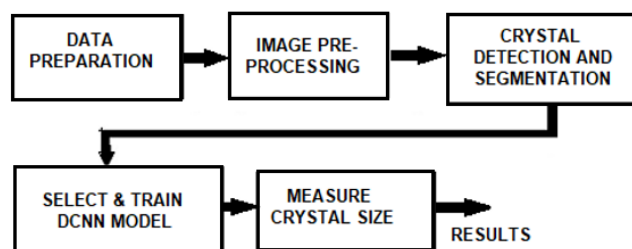


Figure 2

General crystal measurement process as proposed by DeepSeek.

2. – MATERIALS AND METHODS

2.1.- THE APPROACH PROPOSED IN THIS RESEARCH

After analyzing the various state-of-the-art approaches that have been proposed so far to solve the problem of measuring crystals in suspension, in this work a somewhat different approach is proposed and tested, which consists in using a YOLO DCNN to detect the crystals, training it with favourable instances of crystals, selected visually by human analysts and considering how clean are these appearing in the images, avoiding undesirable situations like overlapping of crystals, noise interference and lack of clarity in the contours and having a 2D projection of the crystal that should be approximately rectangular in shape, as would correspond to one side of a crystal with the geometric shape of a prism. An image postprocessing is performed afterwards to improve the images of the isolated crystals provided by YOLO and then the crystals are segmented and measured using conventional Computer Vision; this process is illustrated in Figure 3.

2.2.- DESCRIPTION OF THE PROCESSING STAGES

2.2.1.- IMAGE ACQUISITION AND PRE-PROCESSING

The images were acquired using a DC5-163, model 29AX E250223 microscope and a digital camera Moticam 2000, where the camera pixel side size is 2.2 micrometers (μm) using x4 augmentation, according to the microscope-camera information documents; further measures were made on the basis these data, without using a physical reference in the images. The size of the original images obtained from the camera was 1600 x 1200 pixels. After a selection by visual inspection of the images to be considered as valid for training the DCNN on the basis of their quality, sections of these of size 640 x 640 pixels (as required by YOLO) were extracted by cropping to 1200 x 1200 pixels and re-scaling, resulting in a final pixel side size of 4.125 μm , which is the pixel size to be used to obtain the physical dimensions of the crystals. Data augmentation to increase the training dataset, using the open-source Python library Albumentations [15], was used. In this process, 138 images obtained by cropping the original photographs, each of them containing some visually considered valid crystals, were used for training, a data set increased by means of data augmentation up to 1656 images, 70% of them were used for training, 15% for validation and the remaining 15% for testing. Data augmentation included random horizontal and vertical flips and 90° rotations and a combination of displacement, scaling and rotation with specific limits for each transformation, as well as modifications of hue, saturation and value to increase the variability of the data set. Finally, the images were converted to grayscale to simplify processing and each augmented image had its corresponding annotations file.

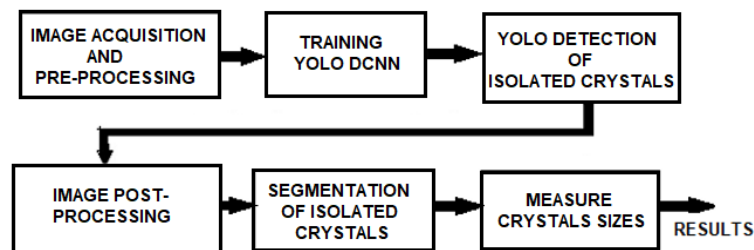


Figure 3

General crystal measurement process as proposed in this work.

2.2.2.-TRAINING THE YOLO DCNN

After analyzing YOLO alternatives [16, 17], YOLO v11 was selected, considering its advantages for the specific application addressed in this work in comparison to other available YOLO versions [17], as for example, among others, better mean Average Precision (mAP), higher processing speed, higher adaptability to various environments and improvements in detecting small objects.

For the process of YOLOv11 training, various essential parameters were configured and employed to ensure a robust and efficient learning process. It is worth to mention on this regard the facts described as follows: (1) keeping during processing the square 640 x 640 pixels size of the images, (2) performing the training during 100 epochs, which implies that the dataset is processed by the model this number of times, to ensure an effective learning to capture adequately the relevant

characteristics of the images, (3) usage of a data file containing fundamental information about the data set, including routes to the images, number of classes and labels names. This file leads the model during the training process ensuring that appropriate data are used always, verifying configuration before training to ensure the existence of the data file containing all the necessary resources and (4) periodic model validation during training, in which validation metrics are printed to check the progress of the process and make adjustments if necessary.

The effectiveness of the trained YOLOv11 system was evaluated using various metrics, and the final evaluation of the effectiveness of the whole system, including both the YOLO detection quality and post processing improvements, was mainly based on the crystal size measures and made use of the confusion matrix (true and false positives and false negatives) to calculate precision, recall and F1 measure [18]. The results obtained in the evaluation of the YOLO training and the system effectiveness are shown in the Results and Discussion Section.

2.2.3.- YOLO DETECTION OF ISOLATED CRYSTALS AND IMAGE POST-PROCESSING

Once the network has been trained, it is ready to perform the detection of crystals, enclosing them into a bounding box, as will be shown in the Results and Discussion section. However, in order to measure the crystals, the images need to be post-processed to prepare adequate conditions for the measurement of the dimensions of crystals.

Post processing the images resulting from the crystal detection has the following purposes: (1) ensure that the images are grayscale, as the bounding boxes introduced in the detection process are colored, (2) discarding the bounding boxes that are cropped due to overlap with the edges of the image, which would result in an incorrect measure of the crystal they contain, (3) discarding bounding boxes whose overlap with other bounding boxes exceeds some threshold (experimentally found) which also could result in altered measures, These procedures were made with the use of standard functions from Python's Skimage and Open CV libraries [19].

2.2.4.- SEGMENTATION AND MEASUREMENT OF THE DIMENSIONS OF ISOLATED CRYSTALS

Once the grayscale images containing only the selected and preprocessed crystals are extracted from the whole 640 x 640 pixels' images (by means of simple morphological operations) and numerous experimental evaluations, it was found that the Otsu multi-threshold segmentation with two thresholds returns a fairly good approximation of the areas occupied by the crystal. This allowed to obtain an appropriate binary mask of each isolated crystal by means of some standard morphological operations: area opening to eliminate small spurious outliers, as well as morphological closing and convex hull to improve the shape of the crystal masks. The binary masks of isolated crystals are integrated in a single image, as will be shown in the Results and Discussion section.

Once the binary mask of a crystal is obtained, the measures from its contours are calculated using resources available in the Python open CV package, following the steps described in [20]. The results sought are length, width and area (of the 2D projection) of the crystal. These measures are obtained initially in pixels and converted to metric units using the pixel size or equivalently the pixels per metric ratio.

3. – RESULTS AND DISCUSSION

The results obtained in the various stages of the process will be illustrated by means of images that will be shown and commented. These do not constitute part of the results of the program, which contains only the final measures of interest for the users, but were created to illustrate graphically the effects of the algorithms employed as described in Figure 3 and explained in section 2.2. YOLO detection and image post-processing results can be appreciated in Figure 4.

Figure 4(a) shows an example of raw image as it is submitted as input to the YOLO DCNN. The result of YOLO detection is shown in Figure 4(b), there every crystal considered as valid for processing according to the quality of the images used for training, appears enclosed in a green bounding box and labeled. The first action using Image Processing tools was to eliminate the bounding box and its label. This was done by obtaining an HSV version of the , creating a binary mask by thresholding the saturation component of it and filling the bounding boxes contours obtained to create a binary mask to select only the images of isolated crystals with a black background; the process includes the elimination of bounding boxes overlapped with the image edges, see Figure 4(c).

- 95% interval during the training validation, and Figure 6b shows the F1 versus confidence curve, which has a maximum F1 value of 0.79 at 0.419 value of confidence, which can be considered satisfactory.

Additionally, an experimental process was performed and the results obtained after the postprocessing of 20 images, not employed in the training process of the YOLO network, were used to obtain the data for the corresponding confusion matrix. Recall that in the postprocessing step, for example, images of detected crystals whose bounding boxes intersect the border of the image and mutilate the crystals are discarded as not valid. The results including True Positives (TP), False Positives (FP), False Negatives (FN) as well as Precision, Recall and F1 measure [18] are shown in Table 1. The obtained indexes values can be considered satisfactory.

Table 1
Performance metrics of the crystals detection with YOLOv11

Crystals total	TP	FP	FN	Precision	Recall	F1 measure
230	212	9	9	95.90	95.90	95.90

Two examples of the presentation of graphs in the final results are shown in Figure 7, obtained from the analysis of ten images which performed the measure of a total of 91 isolated crystals. Figure 7(a) shows the histogram of areas, measured in square micrometers, for this number of crystals, while Figure 7(b) presents a combined histograms graph for lengths and widths of the crystals, both in micrometers.

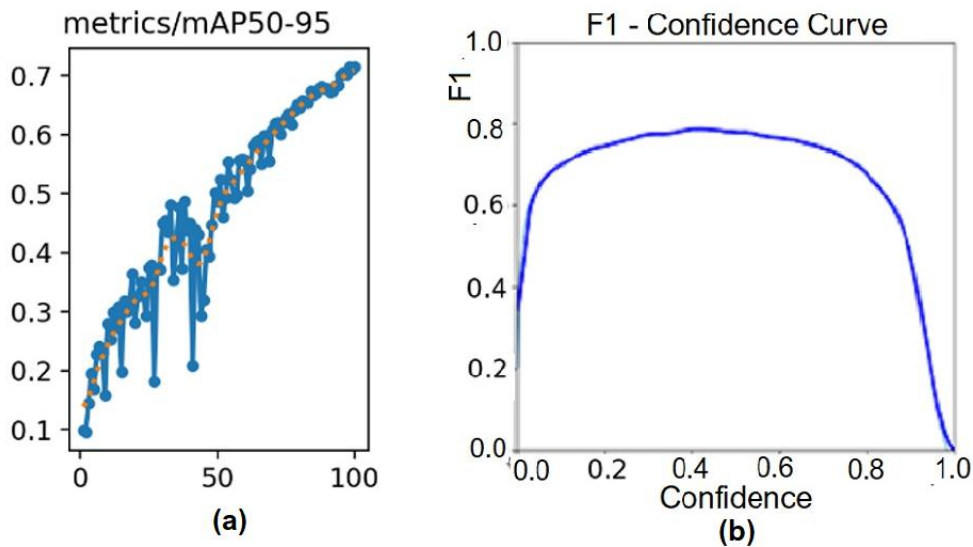


Figure. 6
Some results of the evaluation of the YOLOv11 behavior. (a) Evolution of the mean Average Precision (mAP) in an Intersection over Union (IoU) 50% - 95% interval during the training, (b) F1 measure versus Confidence curve, where the maximum value of F1 is attained at 0.419 Confidence value.

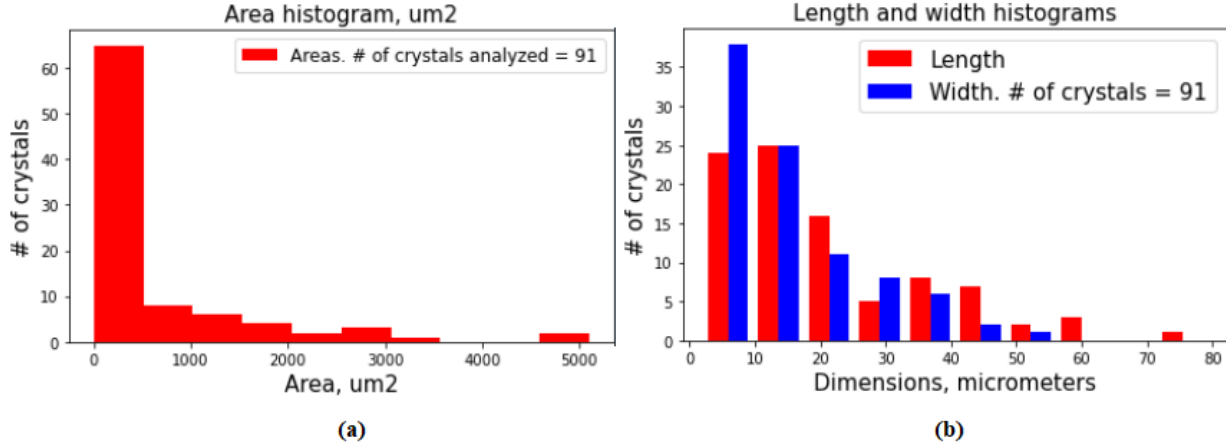


Figure 7
Examples of graphical presentation of the results. (a) Histogram of areas.
(b) Combined histograms for length and width.

The results obtained were compared to a ground truth created manually using the ImageJ software [11], recognizing in this case that the interactive segmentation with ImageJ has an important degree of subjectivity and variability inter and intra-observers, which affects the precision of this evaluation. The evaluation measure employed was the percentage of relative error $\bar{E}$ in the crystal areas measured in pixels, where N is the number of crystals measured, A_i is the calculated area in pixels of the crystal i and A_{iGT} the area of the corresponding ground truth.

$$\bar{E} = \frac{1}{N} \sum_{i=1}^N \frac{|A_i - A_{iGT}|}{A_{iGT}} \quad (1)$$

Analyzing the precision of sugar crystal measurements via image analysis presents several challenges: firstly, the crystals are 3D prisms, whereas the image captures a 2D projection of the crystals in suspension, which might not be suitable for estimating their dimensions. It is expected that the selection of favorable crystals by YOLO will help to mitigate this problem. Furthermore, there is no publicly available image databases of sugar crystals in suspension that researchers can use for comparative purposes. The main sources of errors and possible improvements to reduce these can be considered as follows: (1) the acquisition of the images is an important part of the general process of crystals measurement presented in this work. Therefore, in order to ensure an adequate quality of the images, there should be a good preparation of the samples avoiding the presence of clusters, as well as adequate resolution, illumination and contrast; (2) the measurements of the images by visual inspection using ImageJ, used to build the ground trust, contain intra- and inter-analysts errors due to human subjectivity; in this case, a better set of measures could be obtained considering the mean values of measures obtained by three or more human analysts; (3) imperfections of the segmentation method used to obtain the best-fitted rectangle for each crystal. Other more sophisticated segmentation methods as for example using convolutional neural networks like U-Net, could improve the results at the cost of a higher computational complexity. Here the area of the crystal images was taken as the parameter to express the crystal size, as it is more precise than mean diameter or mean aperture. Taking into account these considerations, the following results were obtained:

A 18% mean value of the relative error in the area measurement of the crystals images was obtained, and this value drops to 14.8% if crystals of area below 2500 μm^2 are not considered, something to be expected taking into account that the subjective effects when building the ground truth might be more significant for small crystals. Notice that the relative error in the area measurement for a given crystal image is, numerically, roughly twice the relative error in the mean diameter or the mean aperture. The values obtained can therefore be considered comparable to others reported in the literature, like in [10], where a 13.4% error is reported using the mean aperture.

4. – CONCLUSIONS

A software tool has been developed in this work, capable of measuring the dimensions of crystals in suspension from photographic images, obtained through a microscope-digital camera system. To accomplish this task, a program was developed using state of the art algorithms in a combination of Computer Vision and Deep Convolutional Neural Networks. The approach employed was compared conceptually with those recommended by the current AI systems ChatGPT and DeepSeek. The YOLO DCNN used here for crystal detection and extraction from the images, contributed to reduce the need of complex filtering algorithms by being trained using favorable (clean and relatively isolated) crystals of various dimensions, which allowed the system to select crystals that share these desirable characteristics. The images of isolated crystals obtained were post-processed by means that involved colormap transformations, various morphological image processing functions and segmentation by Otsu multilevel thresholding, which allowed to obtain binary masks representing the area occupied by the crystals.

Specialized Computer Vision tools were used then to find the rectangles that best approximate the binarized crystal images, whose dimensions are to be measured and their lengths and widths adjusted to have the same area as each crystal binary mask. Finally, the system gathers the measures obtained for an appropriate number of crystals and calculates a group of descriptive statistics (e.g. such as mean value and standard deviation) of length, width and area as well as build histograms of these measures, that are expressed in metric units by using appropriate calibration factors like pixels per micrometer.

The previous description leads to the general conclusion that the system developed satisfies the purpose for which it was created. However, it is to be noticed that in spite of the selection of favorable crystals that the system makes, it is highly desirable to establish a protocol for the acquisition of the images, to ensure a reasonable degree of quality and uniformity in them. What was done in this study also allows space for future work, for example reducing the errors due to subjectivity to obtain a ground truth using ImageJ, as well as the use of other alternatives for segmentation, that could include other conventional methods not yet tested for comparison in this work, or the semantic segmentation method using DCNN.

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CONFLICT OF INTEREST AND AUTHOR RESPONSIBILITY STATEMENTS

The authors declare that there are not conflicts of interest with any institution, organization, or entity that could influence or bias the work presented in this manuscript. The research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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AUTHOR CONTRIBUTIONS

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