THE DIAGNOSTIC OF TWO-PHASE SEPARATION PROCESS USING DIGITAL IMAGE SEGMENTATION ALGORITHMS

Michał Łukiański, Radosław Wajman
Lodz University of Technology, Institute of Applied Computer Science, Łódź, Poland

Abstract. The project aimed to develop and implement algorithms to diagnose the phase separation process based on digital images. The image processing techniques and various numerical methods for interpolation and integration were used to identify the process state. The swirl’s volume and diameters at its three different levels can be determined on-line. A consistent diagnostic signal is produced and can be used by the control unit. The program was written in Python using the OpenCV library that allows the analysis of digital images. The article presents the developed procedure that provides reliable results despite the poor quality of the input source video stream. The complete procedure was described with the results’ presentation and discussion at each step.

Keywords: image analysis, image segmentation, computerized monitoring, separation processes.

1. Introduction

The rapid progress in the development of computer systems has a positive impact on the diagnosis and control instruments for industrial processes [2,6]. Thanks to this, the production may be automated and achieve still greater efficiency and better quality of the final products. An example of this is the phase separation process. It is required to observe and adjust the flow of components to obtain the maximum efficiency. Localization of the sensors inside the chamber (reactor) in which the phase separation takes place, could have a negative effect on the obtained results and interfere with the process. Therefore, non-invasive monitoring is required. To meet such requirements, the video observation with image processing techniques have been applied.

In the case of this project, the process of gas-liquid separation has been observed. The diagnostic output signals of the algorithm are the diameters (taken on three different levels) and the area of the swirl. This information is valuable in further processing to correctly set the phase separation before entering the next part of the pipeline.

1.1. Image capturing

A non-invasive measurement method was used to observe the process. It is highly relevant not to interfere with the process behavior. The camera with a resolution of 1280 x 720 pixels and the ability to capture 100 frames per second was used. The camera lens was set to have a frame only the cyclone. From the collected video streams, 19 images were selected to analyze the most specific types of swirl (Fig. 2), which are numbered for further references and processing.

1.2. Image processing and analysis

Image processing is widely applied in numerous computer diagnostic systems based on digital images. This approach allows automation in the monitoring (i.e., find shapes or features). The most common involved technics are segmentation algorithms. In a frame of this project, the swirl was issued from the background (Fig. 3) [5]. In addition, the image was converted from a gray image to a binary image. The thresholding operations ensured this. In Fig. 3, the complete processing schema is presented. It involves image preparation, swirl identification, and features’ measurement.

Fig. 1. The research facility for two-phase flow separation (cyclone)
2.1. Image preparation

The image preprocessing was developed. The captured frame is held as a three-dimensional matrix. The first two dimensions provide the pixel position, while the third its color level. This format is a commonly used way of image representation in the RGB color space. First, the color information and some parts of the image were removed. To get a grayscale, the arithmetic mean of the color saturation value was calculated. Next, some glares on the cyclone wall were removed. It was done by cropping the edges of the image. Similarly, the images were cropped from the bottom to remove the unformed part of the swirl with random air bubbles.

![Image 1](image1.png)

**Fig. 2.** The 19 images selected from the video stream with the most characteristic swirl types of phases separation

Before the edge detection, the white points that do not belong to the swirl should be removed. For this purpose, the erosion operator was used. Erosion [7] is a morphological operation used in binary images that make objects narrower. The neighborhood of each pixel is checked, and if only one of the neighboring points has a zero value, then the considered point also gets zero. Otherwise, it remains unchanged. Thanks to this, most of the artifacts were removed from the background, and the edges get smoother (Fig. 5a). Nevertheless, the swirl also became narrower as well as the gaps got larger. However, it does not have any negative impact on further analysis because the gaps will be processed in the next stages.

![Image 2](image2.png)

**Fig. 3.** The algorithms schema for image processing applied in the project

2.2. Image processing

The image segmentation [7] is a process that results in the image division into certain areas. These areas contain a set of points – pixels having similar properties due to previously used criteria. The work involves thresholding and edges detection techniques. Due to the noise in the input image, it was not decided to use the edge detection algorithm exclusively.

The swirl is brighter than the background. Unfortunately, the brightness level of the background is not uniform. Therefore, after thresholding, some light reflections and air bubbles are detected incorrectly. Some areas are misclassified, creating gaps. It is because the light source was set on one side of the cyclone and was not dispersed. As a result, the swirl was not uniformly illuminated.

The correct threshold level has a key impact on further analysis. The small value (here 60) reduces the formation of swirl’s gaps in the image but simultaneously produces artifacts, which makes it is difficult to detect the right swirl edges. Finally, the swirl becomes wider (Fig. 4). This matter is caused by the classifying part of the background as the surface of the swirl. However, setting a higher threshold level (i.e., 80) has the opposite effect. Fewer artifacts can be faced, but the gaps became too large and distort the actual swirl shape (Fig. 4 fourth image). Therefore, a medium level (70) was applied what allowed to generate a small number of defects, while reducing the size and amount of interferences.

![Image 3](image3.png)

**Fig. 4.** Images after thresholding with level 60, 70, and 80

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![Image 4](image4.png)

**Fig. 5.** Results of further processing: (a) erosion, (b) edge detection (Fig. 6), (c) edge filtration (Fig. 7)

2.3. Edge detection

Edge detection [7] is one of the basic techniques of image analysis. The purpose of it is to find these points where luminance changes rapidly. In scientific literature, the basic operator of edge detection is based on the Sobel operator. The principle of operation is to use a discrete central difference to obtain the intensity gradients. In this work, it was decided to develop another solution. There is no need to calculate gradients. The object identification in the image is focused on finding the value 1 in the given row and column. Next, other points have assigned value 0. Note, that in this processing, only the outer edges should be identified, but the common edge detection algorithms like Sobel would detect also the edges inside the swirl. Keeping this in mind, the first occurrence of a non-zero value in each row in the image matrix needs to be found. The principles of the proposed solution are depicted in the block diagram below (Fig. 6). The procedure...
depends on the considered side of the swirling edge. For this being on the left side, the algorithm analyses the raw forward and differently for edges on the right. Then, it processes backward. The edges can be found for each side separately. However, still it is possible to observe some white points which do not belong to the swirl (Fig. 5b). These are artifacts not removed by the erosion. Besides, there is an edge in the middle of the swirl that does not reflect its correct shape. In the next processing steps, this may lead to incorrect determination of the interpolation polynomial. For this reason, it was decided to design an algorithm for these points’ filtration (Fig. 7), which additionally examines the local point deviation. For two points, a vector is created. Then, the rake angle is calculated. If the value of this angle is lower than the applied criterion, the point is not rejected. This approach allowed utterly to eliminate the artifacts (see Fig. 5c). Most edge points that could cause irregularities while the interpolation, also were removed.

Moreover, the implemented algorithm has an advantage in comparison to the standard implementations of common edge detection algorithms. It works independently for both swirl sides and can be processed within separate threads what additionally can reduce the processing time. In the future, the optimization at higher resolutions, up to 8K (7680 x 4320 pixels), will be implemented based on the massive parallel computations (nVidia CUDA [3]). It would be possible to divide the image matrix to rows for each swirl side and to run all such slices on separate GPU cores.

3. Swirl identification

The procedure for swirl identification is as follow:
1. Determination of interpolation polynomial,
2. Calculation of two integrals to determine the swirling surface,
3. Determination of the swirl diameter at three levels.

The swirling surface, however, does not provide adequate knowledge about the process. By monitoring the process at selected levels, it is possible to estimate the swirl type. If the process is running correctly, these values should be constant.

3.1. Interpolation of the edge points

Numerical interpolation was used to obtain functions describing the swirl edges. Interpolation [1] is a method of creating new points in a range regarding the known points. The interpolation determines a function that returns known values in given points called nodes. In the considered solution, the known values are the edges points. The numerical method applied to solve this problem uses a two-dimensional Cartesian coordinate system and cannot take negative values. Therefore, the interpolation function should be in the first quarter of the coordinate system. This imposes to consider the point (0,0) in the lower-left corner of the image. Next, the numbers of image’s columns can be mapped on the Y-axis, and numbers of rows on the X-axis (Fig. 8).

The established procedure for swirl area identification reflects its shape and location. It is also fully controllable through a threshold criterion that can be adapted to the needs. Under better scene lighting conditions, more precise results would be expected.

The solution has been tested on a workstation equipped with a third-generation Intel Core i5 processor. The average total computation time for edge detection for a 1080x720 image was only 12 milliseconds. This gives us 83 processed images per second. The algorithm's running time will increase together with the image resolution. However, for the present conditions, it can be considered to work in real-time systems.
Next, the function \textit{polyld} is called. The input argument is
the polynomial coefficients vector. As a result, the interpolant
can be obtained (Fig. 9) that can be joined with the source
image (Fig. 10).

![Fig. 10. Interpolated edges on the source images with determined swirl diameters on three levels (top, middle and bottom)](image)

### 3.2. Calculation of the surface and diameter of the swirl

With the functions describing the edges, it is possible to
calculate the surface of the swirl. Numerical integration by
the Simpson method has been implemented [1]. The Simpson rule for
calculating the value uses equidistant points symmetrically settled
in the range \([a, b]\). The integration range is divided into \(n\) smaller
intervals. The value \(n\) must be even. The resolutions of the digital
images meet the condition of divisibility by two. Next, the areas
under both functions, as integration results, can be subtracted from
each other to determine the swirling surface (Fig. 11).

![Fig. 11. The graphical interpretation of calculated swirl surface](image)

The three levels where the swirl diameter is going to be calculated,
are in the upper, lower and middle parts of the swirl (Fig. 10). The distance between two selected points from the two
interpolated edges is calculated in pixels. This is calibrated regarding
the real cyclone radius that is equal to 17.9 cm. The obtained
results are listed in Table 1. The values 0mm for diameter are in
case of superimposition of two edges. It happens for very thin
swirls.

### 4. Summary

The project aimed to develop and implement the complex
procedure of image processing and analysis algorithms with the
numerical methods to determine the features of the swirl in the
two-phase separation process. The low quality of source input
images forced to develop some new algorithms for edge detection
and noise filtration. The specificity of these algorithms allows us
to implement them to be run within different threads or on
multi-core GPU units.

The interpolation technique was applied and verified by the
superposition of the results and source images. By changing
the order of the interpolation polynomial it is possible to reflect
the swirl shape better. Obtained measurements of characteristic
features of the separation process can now be used as an input
signal to a control unit. The swirl properties were successfully
determined as surface and diameters at three different levels.

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Eng. Michał Łukiański
e-mail: michal lukianski@gmail.com

Michał Łukiański is a graduate of Lodz University of
Technology. His interests lies in image processing,
software engineering for embedded systems, fuzzy
logic and machine learning.

https://orcid.org/0000-0002-4927-5350

D.Sc. Eng. Radosław Wajman
e-mail: radoslaw.wajman@p.lodz.pl

Radosław Wajman is an adjunct at the Institute of
Applied Computer Science at the Lodz University
of Technology. In his work, he deals with the issues
in the field of electrical capacitance tomoigraphy,
fuzzy inference, software engineering, two-phase
gas-liquid flow recognition, image reconstruction,
and recognition.

https://orcid.org/0000-0002-6372-5960

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