Design and Implementation of Image Processing Software for Space Evaporating Droplets (Postprint)

Authors: Feng Yanhui, Yu Qiang

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Abstract

The space droplet evaporation image processing software is designed and developed for investigating space droplet characteristics, serving as a critical data processing platform for the space experiment on evaporation and fluid interface effects aboard the SJ-10 scientific satellite. The software employs edge detection techniques and contour fitting methods to analyze and process droplet images, thereby extracting comprehensive geometric characteristics of the droplets; it utilizes a MySQL database and CSV files for data storage, facilitating data utilization. Experimental results demonstrate that the error range of the obtained droplet geometric characteristics can be controlled within 5%, and the processing time per image can be controlled within 1 second.

Full Text

Design and Implementation of Space Evaporation Droplet Image Processing Software

FENG Yan-hui[1,2], YU Qiang[1]
(1. National Space Science Center, Chinese Academy of Sciences, Beijing 100190, China;
2. University of Chinese Academy of Sciences, Beijing 100049, China)

Abstract

The space evaporation droplet image processing software is designed to investigate the geometrical characteristics of droplets in space, serving as a critical data analysis platform for the evaporation and liquid interfacial effect experiment aboard the SJ-10 scientific satellite. The software employs edge detection techniques and contour fitting methods to analyze droplet images and extract their geometric properties. Data storage is implemented using both MySQL databases and CSV files to facilitate data utilization. Experimental results demonstrate that the software controls measurement errors within 5% and processes each image in less than one second.

Keywords: image processing; droplet geometrical characteristics; edge detection; contour fitting

Introduction

Evaporation and fluid interface effects represent a focal point in international microgravity fluid physics research [1-4]. Chinese researchers have conducted related experiments in drop towers and parabolic flights through collaboration with foreign institutions [5,6]. However, these platforms cannot support long-term observation of droplet evaporation characteristics in microgravity environments. To advance this research, the SJ-10 scientific satellite carries an evaporation and fluid interface effect experimental platform to study phase-change fluid interface processes under microgravity conditions [7]. In this experiment, droplet state evolution is recorded by CCD cameras, necessitating image processing to extract droplet geometric characteristics for data analysis. The space evaporation droplet image processing software implemented in this paper is developed using Qt Creator, enabling cross-platform deployment. It efficiently calculates various droplet geometric characteristics while providing visual display of the dynamic processing sequence and results.

1 Image Processing Software Module Design

Qt Creator is a cross-platform C++ integrated development environment that runs on Windows, Linux, Mac OS, and other desktop operating systems [8]. The image processing software is developed on this platform, facilitating straightforward code portability across systems and enhancing software applicability. Functionally, the software comprises five main modules: file processing, preprocessing, image processing, data processing, and batch processing, as illustrated in Figure 1 [Figure 1: see original paper].

2 File Processing Module

The file processing module handles image loading, saving, and closing operations. The file opening function loads droplet images into the display area, with file filtering and path memory options implemented in the dialog for efficient selection of appropriate images. Path memory is achieved through the QSetting class, which reads and writes path information in INI files as key-value pairs [9]. During image processing, users can save the current processing state for subsequent verification and observation. The program employs an ImgType enumeration to store intermediate image states, with mappings shown in Table 1 . When closing a file, if the processing state is not "FINA," the system prompts users to confirm whether to discard the current image; otherwise, it closes the display area and releases resources.

3 Preprocessing Module

The preprocessing module includes parameter setting and region selection functions. Geometric characteristic calculation requires initial configuration of base height, image scale, and geometric characteristic file paths. Parameter setting is implemented as a modal dialog, with parameters stored as key-value pairs and managed via the QSetting class. Region selection addresses edge noise in non-ideal experimental environments [10] by enabling image cropping to isolate the target region and eliminate interference. The processing logic for region selection is depicted in Figure 2 [Figure 2: see original paper].

4 Image Processing Module

The image processing module performs grayscale conversion, binarization, edge detection, and contour fitting. Original droplet images are RGB three-channel color images, but this complex data structure is not conducive to processing. The software first converts color images to grayscale, then performs binarization, reducing the data from three channels to one for convenient reading and modification. Edge detection, a classic research topic in image processing, provides crucial feature parameters for image interpretation [11]. This software uses the Canny operator for edge detection, which offers good noise immunity and produces thin edges [12], making it widely adopted in engineering practice. The droplet contour obtained through edge detection contains substantial data with redundant information. Sparse extraction reduces data volume and eliminates redundancy through the following steps: (a) obtain the maximum row index maxr of the droplet contour and set current row index r = maxr; (b) acquire the leftmost and rightmost column indices lc and rc for row r, yielding contour coordinates (lc, r) and (rc, r); (c) increment r by 1 and check for boundary violation—if exceeded, sparse extraction terminates; otherwise, return to step (b). Following sparse extraction, contour fitting is performed using an optimization iteration method based on surface tension equations.

5 Data Processing Module

The data processing module calculates geometric characteristics and saves results. For geometric characteristic calculation, the droplet is segmented into multiple frustums using vertical coordinates as division points. Based on the droplet contour curve characteristics, contour points are defined as (,), (,), (,), (,), ···, (,), (,). With image scale , droplet height is h = m ∗ and radius r = − ∗ . Surface area and volume are obtained through integration: surface area S = + (where is the lateral area of the i-th frustum and is the top surface area), and volume V = (where is the volume of the i-th frustum). Contact angle calculation employs the

Young-Laplace equation. As shown in Figure 3 [Figure 3: see original paper] [13], with the droplet apex as origin O, the tangent as x-axis, and its normal as z-axis, O and O represent curvature circle centers at point P, R and R are curvature radii, s is the arc length from P to O, and is the angle between the tangent and data plane. The derived Young-Laplace equation satisfies:

1dx1dz1ds1z1xx1R2R1O2Oz ABo11012sindzdsRx =+−

where R is the curvature radius at point O, with boundary conditions (0) = (0) = (0) = 0. Using the Newton-Raphson iteration method combined with coordinate rotation [14,15], values at each point can be obtained quickly and accurately. The left and right contact angles correspond to values at points A and B, respectively.

For data storage, the software implements dual-path storage for enhanced security. One path uses a MySQL database, an open-source database providing C/C++, Java, and other language interfaces that supports source code portability for cross-platform implementation. Given the moderate data scale, MySQL' s lightweight architecture offers high insertion and query speeds [16], meeting storage requirements. The other path uses CSV (comma-separated values) files, which employ comma delimiters for fields and newline delimiters for records (with non-numeric data enclosed in quotes). As simple structured text files, CSV files facilitate program read/write operations and can be opened in Excel for secondary data processing.

6 Batch Processing Module

The batch processing module handles multiple droplet images under identical experimental conditions. Its processing logic is illustrated in Figure 4 [Figure 4: see original paper]. Preprocessing notices remind users that processing objects must be droplet images from the same experimental condition with identical dimensions, and that parameter settings must be completed before batch processing.

7 Experimental Results

Error measurement validates software accuracy using standard spherical caps as test objects. Based on spherical cap surface area and volume formulas, geometric characteristics corresponding to different central angles are calculated. Tests were conducted on spherical caps with radius 300 and central angles of 130°, 140°, 150°, 160°, and 170°, with measurement errors shown in Table 2 . Results demonstrate that all measurement errors remain within 5%, satisfying data usage requirements.

For experimental validation, a set of droplet images under identical conditions was batch-processed to obtain volume variations shown in Figure 5 [Figure 5: see original paper]. In Figure 5, segment AB represents droplet injection with gradually increasing volume and surface area; BC represents the saturated state where droplet volume and surface area reach maximum under surface tension and gravity; CD represents the evaporation process, showing stable evaporation characteristics. The curve progression conforms to expected droplet injection and evaporation behavior, further verifying measurement accuracy.

8 Conclusion

Developed using the Qt Creator platform with modular design principles, this software demonstrates excellent applicability and reliability. Successful application in droplet image analysis confirms that the software provides researchers with reliable droplet data and meets all design requirements.

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First Author Introduction:
FENG Yan-hui (1990–), male, from Langfang City, Hebei Province, Master' s degree, graduate student, research direction: computer application technology.

Note: Figure translations are in progress. See original paper for figures.