NASA Computational Case Study
Characterizing Moving Particles

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NASA Science Application: Planetary sciences, particle characterization.
Computational Algorithms: (De)Convolution , (inverse) Fourier transform, image deblurring.

1 Introduction

Studying and characterizing small particles, such as dust particles, is of interest to NASA scientists for many applications. A large depth-of-field Particle Image Velocimeter (PIV), with a collection of image analysis based algorithms for particle characterization, was primarily developed at NASA GSFC for characterizing fluxes of dust particles in the Martian atmosphere in particular, and planetary surfaces in general [2,3]. Examples of potential terrestrial applications include monitoring of airborne industrial pollutants and airborne particles in mine shafts.

For small particles, approximately less than 150 μm in diameter, the dust signatures that PIV captures are dominated by rotationally symmetric near-field diffraction patterns, as shown by the falling particle patterns in Figure 1. Several image processing algorithms were designed and developed for PIV in order to characterize dust particles. Characterization algorithms include counting dust particles, determining their locations, sizes, as well as direction and velocity of their movement [2]. In this case study, we will learn how optical properties of traveling dust particles were used for estimating their velocity vectors via image analysis.

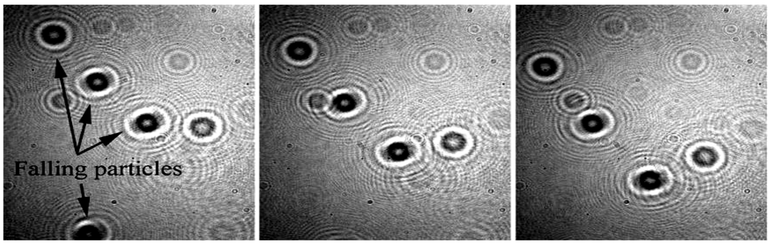

Figure 1: PIV images of 10μm diameter particles in free-fall.

2 Problem Description

Dust particles in absence of motion typically appear as nested circular patterns in PIV images. In this section we learn about optical properties of dust particles in presence of motion. We also learn how to utilize these properties to determine the travel direction and velocity of a moving dust particle. We work with a simulated dust particle of size 250μm, Image I, that is stored in 'SIMPBYTSCL15.tiff' file.

Activity 0: Read Image I into a two-dimensional array from the provided 'SIMPBYTSCL15.tiff' file. Report number of rows, columns, and type of the read data.
Hint: You can use the open source Matlab routine called 'tiffread2' (available from Matlab Central), or implement its equivalent, and then extract and save the 'data' field from the 'stack' portion.

In the next two activities, we simulate how a dust particle moving horizontally might appear in an image.

Activity 1: Construct Image B of the same size and data type as Image I, such that all its pixels are black except a horizontal line of seven pixels, located at the center of the image. We call B a *horizontal filter*. Convolve Image I with Image B. How does the resulting image, BI, compare to image B?
Hint: Use 'conv2' routine of Matlab or implement its equivalent.

Activity 2: Repeat the same exercise with horizontal filters of lengths equal to 5, 9, 11, and 13 pixels each. Save and visualize the results as .tiff images. How does the filter length affect the results?
Hint 1: What happens to the brightest and darkest areas of the image?
Hint 2: How does the shape of the dust particle relate to the filter size?

Now we investigate motion in other directions.

Activity 3: Consider the horizontal filter of seven pixels centered at the middle of the image again. Convolve the original image I with this filter rotated, such that it makes a 30, 60, and then 90 degree angle in counter-clockwise direction with the horizontal line passing through the center of the image. Visualize and save the results in .tiff images. How does the rotation affect the results?
Hint 1: Use 'imrotate' routine of Matlab or implement its equivalent to get an image of the rotated filter with the same dimensions as the original image.
Hint 2: Where are the brightest areas in the results? In what direction these areas appear?
Hint 3: Does the particle elongate in any particular direction?

You just experienced blurring a clear image I, with a blurring filter B. When an image is blurry, it means that the original clear image was convolved with some blur function or filter. If we have some knowledge of the properties of the blurring function or filter, we can restore the clear image. We refer to this process as *deblurring*. One can use the information about the blurring filter or function to *deconvolve* the blurred image and retrieve the original clear image. For moving particles, the blurring filter is directly related to the velocity vector of that particle. That is, the direction and velocity of moving dust particles contribute to the appearance and shape of their blurry images. Thus, if we estimate the blurring filter correctly, we then know the direction and velocity of the traveling particle.

Question 1: Suppose we know the blurring filter. Derive the mathematical equation yielding the clear image from the blurred image and its blurring filter. What is a potential problem with using this approach for estimating the clear image?
Hint: Use the Convolution theorem and properties of the Fourier transforms [4]. Recall, that the convolution theorem states that the Fourier transform of the convolution of two matrices is the Schur (entry-wise) product of their Fourier transforms. In other words, if C is obtained by convolving matrix A with matrix B, then the following holds.

$$\begin{aligned} C &= A * B \\ \text{FFT}(C) &= \text{FFT}(A) \times \text{FFT}(B), \end{aligned}$$

where * represents the convolution and × represents the Schur product.

Activity 4: Consider the provided blurred image ‘bImage.tiff’. Visualize the blurred particle in gray scale values. Estimate the travel direction of the dust particle.
Hint 1: The travel direction of a dust particle is the same as the direction of its blurring filter.
Hint 2: Use what you learned from Activity 3 about the relationship between the direction of the filter and properties of the blurred image of a dust particle.

Activity 5: Deblur the blurred dust particle saved in ‘bImage.tiff’ file. Visualize and save the clear image in a .tiff file. Report the travel velocity of this particle.
Hint 1: The travel velocity is a function of the blurring filter’s length. Report the velocity in terms of the blurring filter’s length in pixels.
Hint 2: Use the Convolution theorem and your answer to Question 1.
Hint 3: Use your results from Activity 4 regarding the travel direction of the particle.
Hint 4: Once you know the direction of the filter, all you need to do is estimate its correct length. Assuming the exposure time of the camera can result in filters of size 1 to 15 pixels before a particle moves out of the frame completely, find the length of the blurring filter in pixels. That is, do an exhaustive search among possible filter lengths and choose the one that minimizes an appropriate error function.
Hint 5: Place filters at the center of an image of size 512×512 with all background pixel values equal to zero.

Extra Credit Activity: Can you deblur the same image using another technique? Can you do so without making any assumptions about the direction or length of the filter? What assumptions did you make? How well does your algorithm work in presence of noise in the blurred image?
Hint: You may benefit from publications on Lucy-Richardson filter [1, 5], Wiener-Helstorm filter [7, 8], or deblurring algorithms [6].

References

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