

Pore Image Processor

The screenshot displays the Pore Image Processor GUI. On the left, the 'Image Processing Commands' panel includes sections for 'Original Image' (filename: d:\wader171_in_150kb.jpg), 'Cropping' (with 'To current axes limits' checked and 'Go' button), 'Background Correction' (Filter Size: 200 pixels, Threshold: 187 > 10 > -78, 'Go' button), 'Binary Operations' (Disk, Square, Custom, Current SE: +, buttons: Erode, Dilate, Open, Close, Majority), and 'Algorithm Log'. The central image shows a grayscale pore image with red outlines and a purple selection box. The 'Results' panel at the bottom features an 'Update Results' button, a histogram, and a data table.

| | # | Diameter | Area | Major Axis | Minor Axis |
|----------------|----|-------------|----------------|--------------|-------------|
| Selected Pore: | 58 | 42.6 | 1428.0 | 52.6 | 35.4 |
| Mean Pore: | - | 31.0 +- 7.5 | 796.5 +- 389.0 | 36.1 +- 11.3 | 27.6 +- 5.9 |

View: Original Image (cropped) Background Corrected Image Current Black & White Image Show Pore Boundaries

Quick Start

1. Launch GUI by typing `launchPoreImageProcessor` at the MATLAB command prompt.
2. Maximize GUI window.
3. Load the image you want to process by clicking on the '...' button in the *Original Image* panel of the GUI window.
4. Crop the image to remove any scale bars or serious edge lighting anomalies either by
 - a. by zooming in on the region you want to keep, or
 - b. by specifying the x and y limits directly in the edit boxesThen press the 'Go' button in the *Cropping* panel to actually crop.
5. Click the 'Show Filter' checkbox in the *Background Correction* panel and make sure that the green square which appears in the upper left hand corner of the image is noticeably larger than the pores in the image. If not, increase the size of the filter until it is.
6. When the filter size is determined, uncheck the 'Show Filter' box and press the 'Go' button in the *Background Correction* panel. Wait for the status message at the bottom of the window to indicate that background correction is complete (generally <20s now).
7. Experiment with various threshold values until you find one that seems to do a reasonable job of visually separating pores from background.
8. Use any binary image operations you like (see the Binary Operations section of this document for explanations of what they all do, but I suggest starting with the 'Majority' operation to clean

up the background noise and solidify the pores). To mimic the default behavior of `findpores.m`, you'd press 'Majority', then 'Erode' twice, then 'Dilate' four times.

9. To select the structuring element used by the binary operations select either the disk or square radio buttons (Custom is not yet implemented and may not be necessary) and specify the relevant dimension in the associated edit box. The current structuring element is shown in the Current SE box, with a one pixel black border around it. 'Majority' doesn't use a structuring element, but the other four do.
10. When you are satisfied that the white objects in the image are pores (or that you've done the best you can), calculate results by clicking the 'Update Results' button on the left side of the *Results* panel. If the calibration checkbox beneath it is checked, the given pixels/nm calibration will be used and the results will be displayed with nanometer units, otherwise the results will be in pixel units. The histogram is of pore equivalent diameters, in the same units as the rest of the results.
11. At any time, you can change the image you are looking at by changing the radio button selection in the *View* panel. In addition, you can toggle plotting of the pore boundaries by checking and unchecking the 'Show Pore Boundaries' checkbox in the *View* panel.
12. If you are unsatisfied with the quality of the results you can start over by
 - a. reloading the original image (resets all images)
 - b. applying background correction (resets background corrected image and B&W image)
 - c. applying a threshold (resets the black and white image)
 - d. applying a binary operation (just continues from where you left off)

At this point you can apply any new processing steps you'd like, and then recalculate the results.

13. At any time after results have been calculated, you can select a particular pore for closer examination by clicking on it. Individual pore characteristics for this pore are then displayed in the table in the *Results* panel, and the pore outline is highlighted in purple and white.
14. At any time after results have been calculated, you can remove a misidentified pore from analysis by
 - a. double-clicking it (with zooming off), or
 - b. selecting it, then clicking the 'Remove' button in the table in the *Results* panel.
15. At any time, you can capture an image of the main axes and save it to a file by pressing the 'i' key (see the Note after Keyboard Shortcuts in this document for exceptions).
16. At any time after results have been calculated, you can save the results structure to a file by pressing the 's' key.

Installation

To install Pore Image Processor, unzip the `PoreImageProcessorGUI.zip` file into a directory on your machine. This directory will now contain the main Pore Image Processor m-files, as well as two

directories containing supporting m-files, called 'OnPath' and 'GUI Tools'. In order for Pore Image Processor to work correctly, the m-files in these supporting directories must be accessible to Pore Image Processor. The suggested method for achieving this is to place these two directories on your MATLAB path, however, if you would prefer, you can simply put all the m-files in a single directory instead.

To launch Pore Image Processor, open MATLAB and make your installation directory the current working directory. At the command prompt, type `launchPoreImageProcessor` and press enter.

Keyboard Shortcuts

| Key | Action |
|----------|--|
| z | Toggle zooming state |
| b | Toggle display of pore boundaries |
| r | Recalculate results |
| s | Save current results to a file |
| i | Capture current image and save to file |

NOTE: Keyboard shortcuts can be a little iffy in MATLAB for a variety of reasons.

- If zooming is on, the zoom function replaces the figure's `KeyPressFcn` and doesn't allow you to modify it until zooming is turned back off, so no keyboard shortcuts will generally work when zooming is on. However, I have modified MATLAB's zoom function code to at least allow pressing 'z' to turn zooming back off. So, if you're using my modified zoom function, then you can turn zoom off by pressing 'z' again. If not, the other way to turn it off is to click the depressed magnifying glass in the figure toolbar.
- In addition, irrespective of zooming, if you've just clicked on a uicontrol, and then type a key, that uicontrol's `KeyPressFcn` is activated rather than the figure's, so you also get no result.
- The take-home message is, if the keyboard shortcut you're using isn't working, make sure zooming is off, and click once somewhere in the GUI window which is not occupied by a uicontrol or axes (panels are just fine).

The Results Structure

After processing, all calculated results are stored in a MATLAB structure. This structure has information about each individual pore, as well as aggregate statistics about all the pores. The following table details each field of the results structure and describes the field contents.

| Field Name | Contents |
|--------------|---|
| pores | A 1xN structure where <code>pores(i)</code> contains data for the <i>i</i> th pore, including the equivalent diameter (field name EquivDiameter), area (Area), major and minor axis lengths (MajorAxisLength and MinorAxisLength), and centroid (Centroid), all of which are in pixel units |

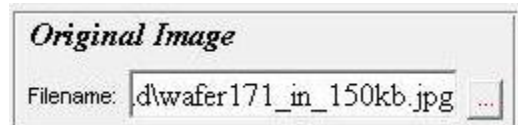
| | |
|-----------------|---|
| pixpernm | either a scalar which contains the pixel/nm calibration used in calculating the nanometer units statistics, or an empty matrix, signaling that no calibration was used |
| stats | A structure which contains aggregate statistical data about the identified pores in pixel units, including: mean, standard deviation, and maximum of the pore equivalent diameter (field names: mean_diam , std_diam , and max_diam), mean, standard deviation and maximum area (mean_area , std_area , and max_area), mean, std. dev. and max for the major and minor axis lengths (mean_majax , std_majax , max_majax , and mean_minax , std_minax , and max_minax , respectively), and the pore density (poredensity) and porosity (porosity). |
| nmstats | A structure which is only present if a pixels/nm calibration has been supplied. If present it contains the same information as results.stats with the same field names, but with the data in nanometer units rather than pixel units. That is, all length measurements have been divided by results.pixpernm, and all area measurements have been divided by results.pixpernm squared. |

Panel Descriptions

Here you can find a more detailed discussion of all the components of Pore Image Processor.

Original Image Panel

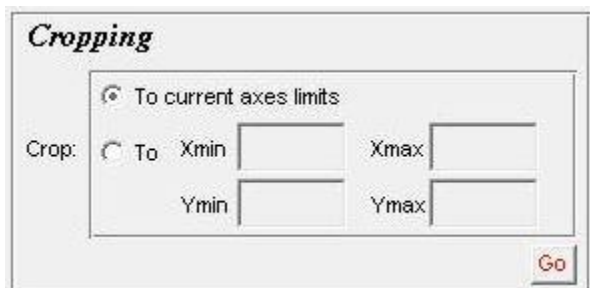
The original image panel allows loading of a new original image into Pore Image Processor. A filename or path and filename can be entered directly into the edit box, or a file can be selected by browsing for it using the ‘...’ button.



Pressing enter in the edit box triggers loading, or loading occurs automatically if a browsed file is selected. If an image file was already being processed, then loading a new image resets all derived images (the background-corrected image and binary image), but does not delete the existing results structure (in case you forgot to save it).

Cropping Panel

Cropping of the original image is often necessary to remove image artifacts like scale bars which can locally throw off background correction or can be misidentified as pores. Pore Image Processor allows two ways to indicate the area you want to keep for analysis. First, you can change the axes limits (for example, by zooming) until the desired area is what is displayed on the axes. Alternatively,



you can specify each of the limits individually in the edit boxes provided. Note that 'Ymax' is intended to refer to the maximum row value desired to be included, which in image display is towards the bottom (because images are traditionally displayed with the origin at the upper left). Likewise 'Ymin' should be

the minimum row number (uppermost row) to include in the cropped image. All of the cropping limits should be greater than or equal to one.

Pressing the 'Go' button in the Cropping panel applies the indicated cropping to the original image. The method used is determined by the radio button selection. Cropping resets the background corrected image and the black and white image.

After cropping is applied, the original image view will show the cropped original image. If cropping is applied again, it will crop the existing cropped image, not the original image loaded from a file.

Background Correction Panel

Background correction is almost always necessary, even if image lighting appears even to the eye. The method of background correction is essentially to subtract from each image pixel the average value of all the pixels in a local neighborhood around that pixel. This means that a background pixel with average intensity will have an intensity of about zero after background correction, and pore pixels, which are generally brighter than other pixels in their neighborhood will have an intensity somewhat greater than zero (how much depends how much brighter they are). The primary question in background correction is how big the neighborhood should be. Ideally, the neighborhood (defined by an averaging filter) should be so large that size of the image features you care about (the pores) is insignificant compared to the size of the filter, and also so small that the neighborhood size is insignificant compared to the gradient in background lighting (i.e. the change in background lighting within any one neighborhood is negligible). Obviously, these are conflicting demands, but the first is more important, since if the neighborhood size is smaller than the image feature size, then your image features will simply be subtracted away and will not come out greater than zero. Generally, a good filter size is a few times the size of your larger pores.



Pore Image Processor allows you to see the current size of the neighborhood on the image directly by checking the 'Show filter on image' checkbox. This allows you to visually compare the size of the filter to the size of the pores without needing to measure pore size at all.

When satisfied with a filter size, click the 'Go' button in this panel to start background correction. Background correction is generally the slowest single step in processing, so be patient. Processing time increases with the size of the image and the size of the filter, but even for a large image and large filter, I wouldn't expect it to take more than a few minutes. When background correction has finished, the status message at the bottom of the GUI window will change from 'Correcting background...' to 'Background corrected'. The view will automatically be updated to show the background corrected image.

Currently, a quick pass with a small median filter to remove salt and pepper noise is included at the start of background correction. I can't think of any reason this would be undesirable, but if you can, this feature can be made optional.

Threshold Panel

Applying a threshold to the background corrected image is the first and probably most important step in correctly identifying pores. An ideal threshold would be a value that all pore pixels fell above and all background pixels fell below. Generally this is not possible, so the goal of choosing the threshold value is to select the one which comes closest to this ideal, where most pore pixels fall above, and most background pixels fall below. Generally, input images come in as truecolor uint8 images, which means that all intensity values are integers. Background correction preserves the class of the image (until the background subtraction, which requires use of negative numbers), and so the image being thresholded is composed of integer intensity values. In this case, there's no point in trying fractional threshold values (i.e. 11 produces exactly the same result as 11.9);



Threshold values are generally determined by trial and error, but good threshold values for fairly dim pores seem to be about 8-12 and for very bright pores can be >50. A good threshold value will always be >0, because of the method used for background correction.

Binary Operations

After thresholding, the binary image generated can be refined to better identify pores using several binary operations. Many of these operations use a structuring element to determine the extent of their effect.

What is a structuring element?

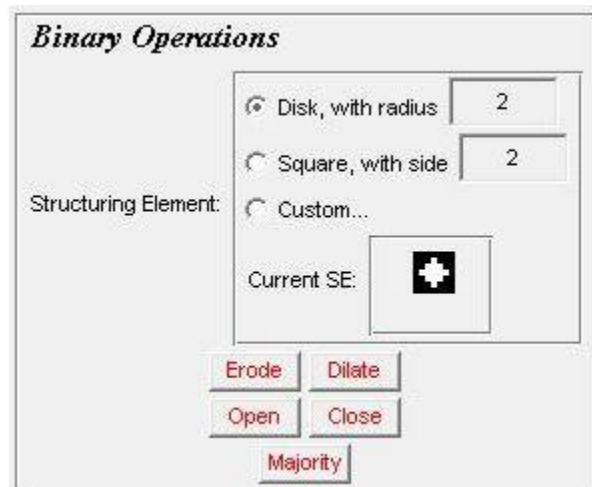
A structuring element (SE) defines a logical matrix which determines which neighboring pixels the value of a particular pixel affects during binary operations. If we imagine that the pixel under consideration is at the center of the structuring element matrix, all other elements of this matrix which are 1 are affected during the operation. For example, if the structuring element neighborhood was

| | | |
|---|---|---|
| 0 | 0 | 1 |
| 0 | 1 | 0 |
| 0 | 0 | 0 |

then the only the pixel to the northeast of the pixel under consideration would be affected by the value of that center pixel. This will be clearer after reading the description of the image processing operations in which structuring elements are used.

Erode

The erode operation changes any white pixels in a defined relation to a black pixel into a black pixel. This relation is defined by the relation of the neighborhood pixels to the center pixel in the structuring



element. For example, using the structuring element defined above, any white pixel which is to the northeast of a black pixel would become black. Repeated erosion of a binary image with this structuring element would have the effect of eating away all white regions from the southwest. A more symmetric structuring element (such as one shaped like a disk) would eat away (erode) the white regions from all directions, by the disk radius in each pass. For a precise definition of erosion and dilation, see <http://www.ph.tn.tudelft.nl/Courses/FIP/noframes/fip-Morpholo.html>. For most purposes, it is sufficient to know that, using a symmetric disk-shaped structuring element, erosion shrinks objects by the radius of the structuring element and that objects smaller than the structuring element disappear completely.

Dilate

The dilate operation is the inverse of the erode operation. All black pixels standing in a defined relation to a white pixel become white. The neighborhood is again defined by the structuring element. For example, using the structuring element defined above, any black pixel with a white pixel to the northeast of it would become white after a dilate operation. Repeated dilation of a binary image with this structuring element would result in all white regions growing to the southwest. A more symmetric structuring element, such as a disk, would grow (dilate) the white regions in all directions, but the disk radius in each pass. Dilation and erosion are complementary operations; dilation of objects is the same as erosion of the background with an inverted structuring element, and erosion of objects is the same as dilation of the background with an inverted structuring element. For a precise definition of erosion and dilation, see <http://www.ph.tn.tudelft.nl/Courses/FIP/noframes/fip-Morpholo.html>. For most purposes it's sufficient to know that dilation with a symmetric structuring element grows the outside of objects by the radius of the structuring element.

Open

The open operation is the combination of an erode operation followed by a dilate operation, using the same structuring element for each. The net effect, with a disk structuring element, is to eliminate narrow white areas while leaving wider white areas more or less unaffected. 'Narrow' in this case is defined as smaller than the structuring element disk diameter. This result is achieved because the erosion changes the narrow white areas completely to black while only shrinking wider areas, and the following dilation grows the remaining areas by the same amount they shrank.

Close

The close operation is the combination of a dilate operation, followed by an erode operation, using the same structuring element for each. The net effect, with a disk structuring element, is to link objects which are separated by narrow black areas while leaving the rest of the objects more or less unaffected. 'Narrow' means smaller than the structuring element diameter. The linking result is achieved because the narrow black areas disappear completely in the dilation and the following erosion does not restore them.

Majority

The majority operation does not use a structuring element. Rather, a pixel becomes white (regardless of its current state) if a majority of its 8-connected neighbors is white and becomes black otherwise. This

has the effect of reinforcing areas of local white pixel density and eliminating white pixels in low density areas. This behavior is perfect for cleaning up background white pixels and reinforcing pore white pixels. In fact, choosing a good threshold and then just applying the majority operation repeatedly can get you pretty close to reasonable pore identification. As currently implemented, this operation is repeated until the image stops changing, although this behavior can easily be changed if users would like to do one operation at a time.

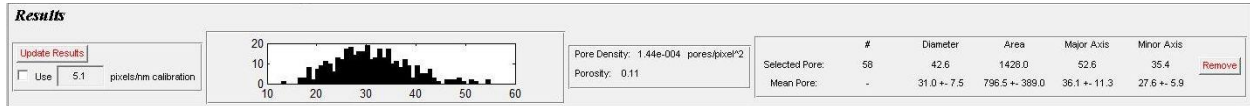
Algorithm Log

This feature is not yet implemented. The idea is to record the processing steps that the user goes through in identifying pore boundaries to three ends:

1. So that the processing steps can be saved with the results. This way, if results are obtained for a particular image in two different ways, one can find which results came from which processing algorithm.
2. So that a processing algorithm which worked well on one image and was saved can be simply loaded and applied to another, rather than forcing the user to apply all the steps manually.
3. To serve as a record for the user of what he has already done in this session ('Did I crop the image yet?..')

I'm working on it.

Results



This panel summarizes the calculated pore information and allows you to update the results based on the most current binary image.

Update Results

Clicking on the 'Update Results' button recalculates all the pore information based on the most recent binary image. If the checkbox beneath the button is checked, the indicated calibration is used and all pore information uses nanometer units, otherwise the results are reported in pixel units. The calibration is set only when results are recalculated, so simply changing the calibration number in the edit box or checking the checkbox will not update the pore data; you must also click the 'Update Results' button.

Histogram

The results histogram shows the pore equivalent diameter vs. the number of pores which have that diameter. The histogram is nanometer-calibrated if the results are nanometer-calibrated. Labels are omitted so that the axis size can be maximized. If you need a larger or annotated histogram figure, you can use the `histFromResults` function as follows:

1. Save the current results from Pore Image Processor by using the 'r' shortcut key.

2. Type `histFromResults` at the command prompt and hit enter. (Or use `histFromResults([], numbins)` to specify the number of histogram bins you'd like to use, default is 50)
3. Select the results file you just saved.
4. View histogram. If the formatting is not to your liking, just edit `histFromResults.m` to set it up exactly as you'd like, or edit the figure directly.

Summary Results

This displays the pore density (# identified pores/processed area) and the porosity (pore area/processed area). The pore density units is an easy place to check whether a nanometer calibration was supplied the last time the results were updated.

Results Table

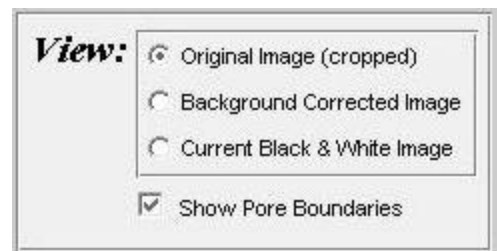
This table shows the pore data for a single selected pore, and the mean data for all the identified pores. Mean pore data is given +/- the standard deviation. As currently implemented, the table shows the pore number (for the selected pore), equivalent diameter, area, and major and minor axis lengths, but these can easily be altered to show any desired results. Data is nanometer calibrated if the results were nanometer-calibrated last time they were updated.

Pressing the 'Remove' button at the right end of the selected pore row removes the currently selected pore from analysis. This occurs by removing the corresponding white region from the current binary image and recalculating the results. This recalculation is automatic and the histogram and table are updated with the new results. A pore can also be removed from analysis by double-clicking it on the image itself (with zooming off, otherwise clicking in the image just controls zooming).

The results table is updated whenever the selected pore changes, a pore is removed, or the results are updated.

View Panel

The view panel is used to switch the image being shown on the main axes and to toggle the pore boundary display on those axes. Selecting a radio button displays the indicated image. Checking the 'Show Pore Boundaries' box calculates the current pore boundaries and plots them on the image in red. The pore boundary display can also be toggled using the keyboard shortcut 'b'.



The primary usage of the view panel is to see the pore boundaries overlaid on the original and background corrected images, in order to evaluate the quality of pore identification. It is often helpful to zoom in on individual pores to examine them more closely.

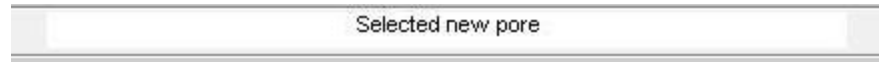
It's also fun to turn off pore boundary display, look at the original image, then click on a pore to select it. If it was identified, it becomes the selected pore, and you see only its outline.

Image Panel

The image panel is mostly for display, but you can use keyboard shortcuts here, select or remove a pore with the mouse, and zoom in on image regions. One thing to be careful of is that double clicking in the image can have two different effects. If zooming is on, then double clicking resets the zoom to the full axes, whereas if zooming is off, double clicking selects and then removes the pore which has been clicked.

Status Panel

The status panel displays messages to keep you



informed about what Pore Image Processor is doing. Essentially any time you ask Pore Image Processor to do something, a related message indicating task progress, completion, or errors should appear in the status message area of the status panel.