Im2mesh_GUI Tutorial

Jiexian Ma*

This is a tutorial for Im2mesh_GUI v2.01, which is developed by Jiexian Ma. Im2mesh_GUI is a graphical user interface (GUI) version of Im2mesh, a MATLAB-based tool.[1] It's used to generate finite element meshes based on 2D multi-phase image. With GUI, Im2mesh becomes much easier to use. User-friendly! It has incorporated many features, e.g., polyline smoothing and simplification. Through this tutorial, you will understand the workflow and the parameters of Im2mesh_GUI.

Installation

Im2mesh_GUI can be installed in two ways: MATLAB app or standalone desktop application.

For using as MATLAB app, you need to install MATLAB software, Image Processing Toolbox, and Mapping Toolbox. When MATLAB software is opened, you can install Im2mesh_GUI by double clicking "Im2mesh_GUI.mlappinstall". After installation, you should be able to find Im2mesh_GUI in the APPS tab of MATLAB.

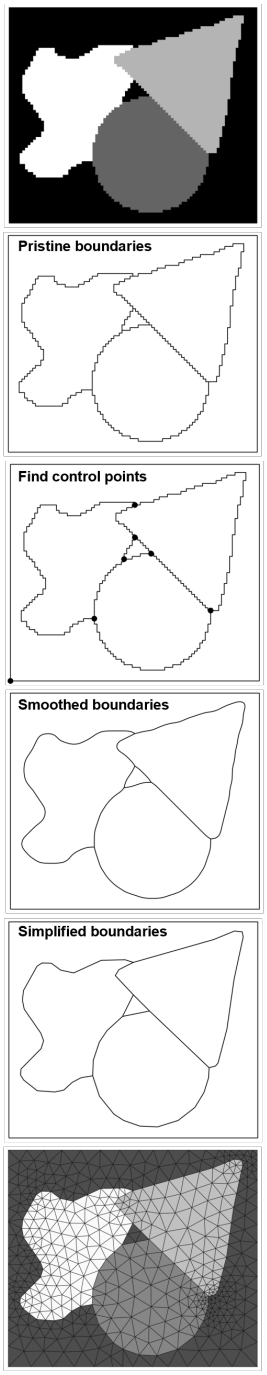
For standalone desktop application, you don't need to install MATLAB software or any MATLAB toolbox. However, you need to install MATLAB Runtime (version 9.11). When you open "Installer_Im2mesh_GUI.exe", the installer will automatically download and install MATLAB Runtime for you. Note that MATLAB Runtime is free. After installation, you can find the application in the following file directory: `C:\Program Files\Im2mesh_GUI\application\Im2mesh_GUI.exe`. When you start the application for the first time, it may take some time to initialize. Just be patient.

Workflow

Figure 1 shows the workflow of Im2mesh. The workflow is straightforward. The GUI window has organized according to the workflow (Figure 2). The workflow consists of 9 steps. Some steps are optional: step 2, step 5, and step 7. When running Im2mesh_GUI, you can skip those optional steps if they doesn't work for your image.

*mjx0799@gmail.com

[1]https://www.mathworks.com/matlabcentral/fileexchange/71772-im2mesh-2d-image-to-triangular-meshes



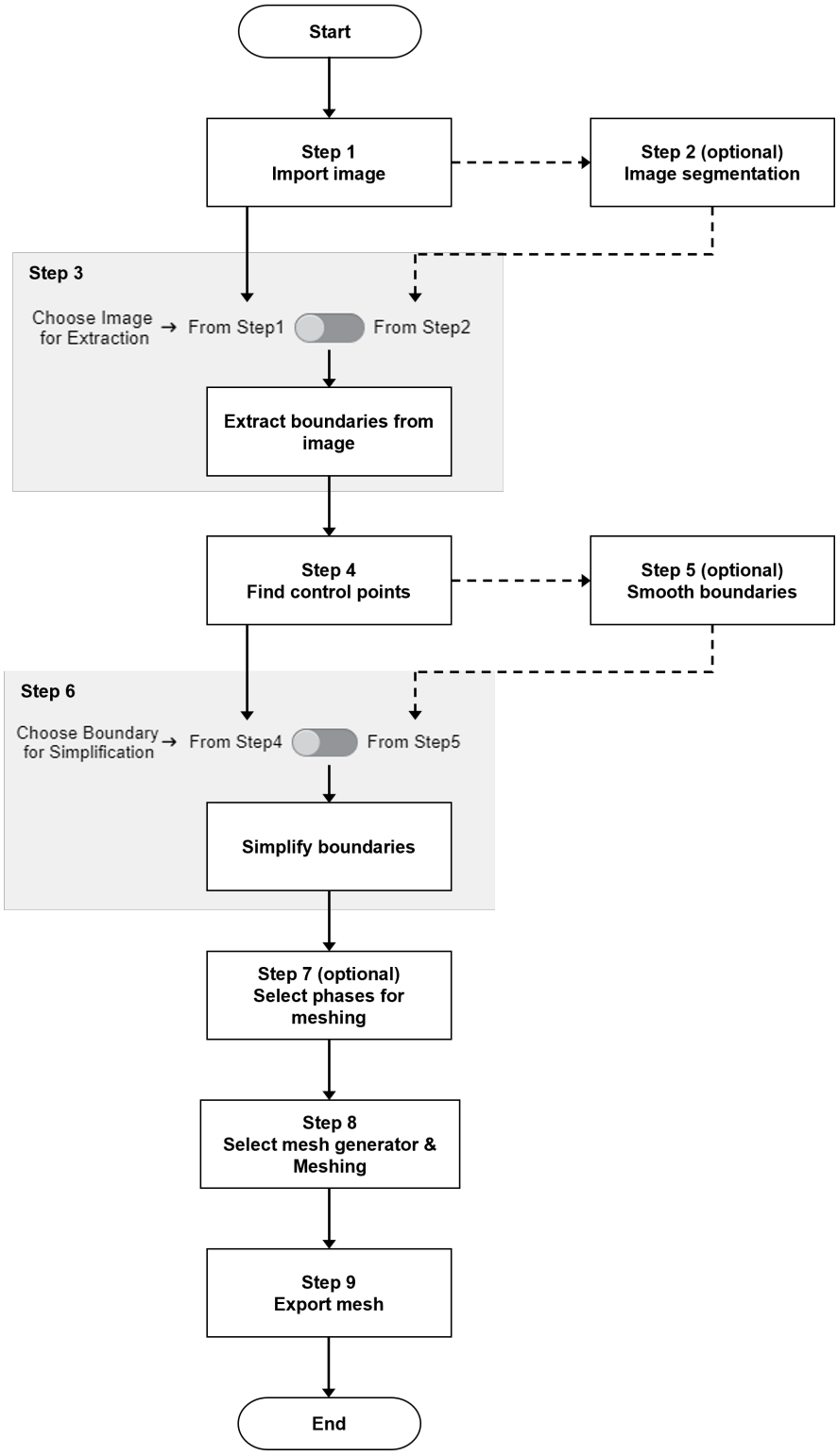


Figure 1: Workflow of Im2mesh

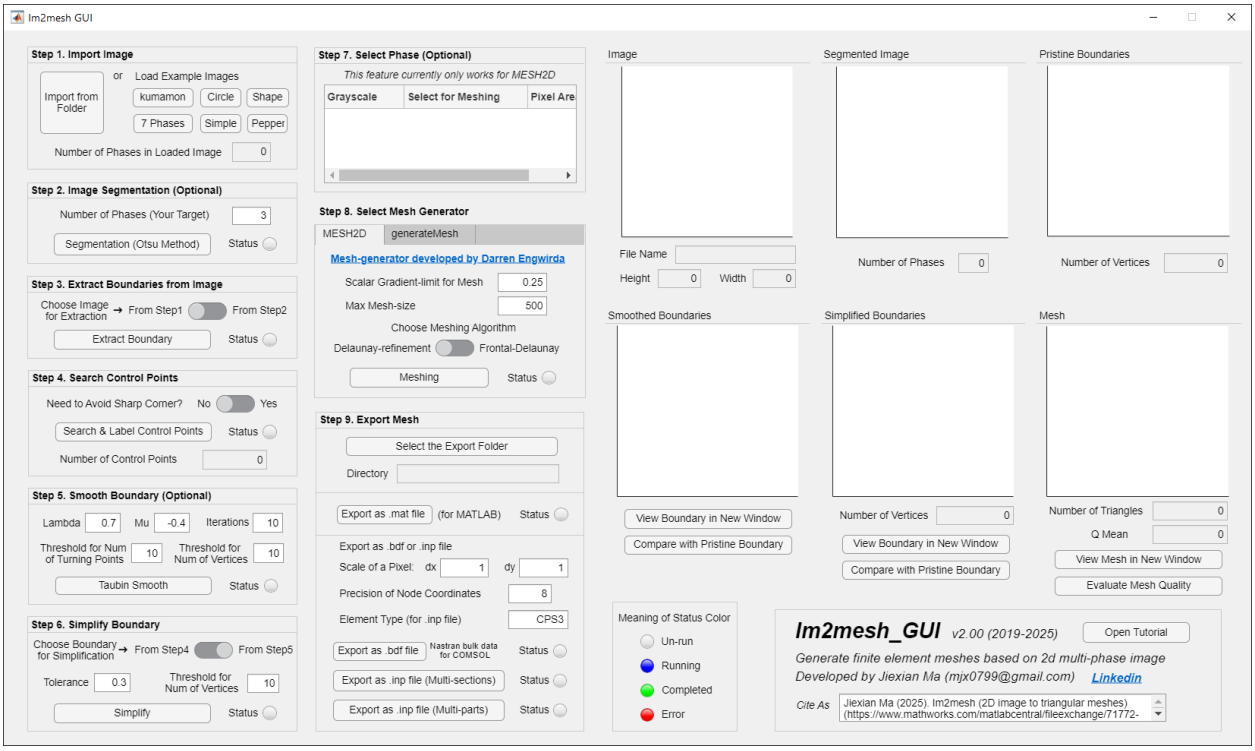


Figure 2: Im2mesh_GUI

Step-by-step Guide

Step 0. Image processing. It's often necessary to perform digital image processing to your raw image. For example, converting to 8-bit grayscale image, noise removal, and image segmentation. You can refer to the following links about how to perform image processing in MATLAB:

`https://www.mathworks.com/help/images/noise-removal.html`
`https://www.mathworks.com/discovery/image-segmentation.html`
`https://www.mathworks.com/help/images/image-segmentation.html`

Step 1. Import image. You can import from your folder, or just load one of the example images. An ideal input image for Im2mesh is a segmented grayscale image. That's because Im2mesh identifies different material phases in an image by their grayscales. Different grayscales correspond to different material phases. If you have 4 levels of grayscale in an image, the resulting meshes will contain 4 phases.

Step 2. Image segmentation. This step is optional. I include this step just for convenience. If you don't need segmentation, just skip this step.

Step 3. Extract polygonal boundaries from image. You can choose your input for this step by clicking the Switch. For example, if your input is from Step 2, just click the

right side of the switch. This step uses a subroutine (`getExactBounds.m`) developed by me to extract the exact boundary from the image.

Step 4. Search & label control points. Here, control point is defined as the intersection or meeting point between edges in the images (Figure 3). These control points will not change their positions (x, y coordinates) in the following steps. This step uses a subroutine (`getCtrlPnts.m`) developed by me to search and label control points.

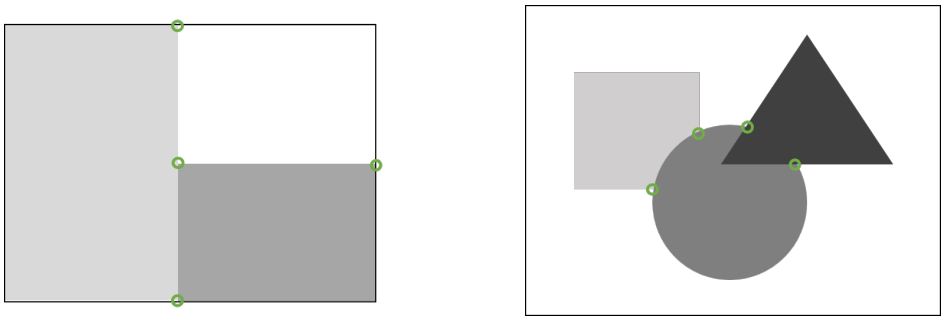


Figure 3: Examples of control points, which are marked with small circles.

I include an option "Need to Avoid Sharp Corners?" in this step. You can set this option to "Yes" in the following case:

- If you want to avoid sharp corner during boundary smoothing and simplification
- If you find the step of mesh generation has failed for your image
- To avoid bugs

Step 5. Smooth boundary. This step is optional. If your polygonal boundaries don't need smoothing, just skip this step. Note that I found boundary smoothing is beneficial in most cases. This step uses 2D Taubin smoothing method (`taubinSmooth.m`), which can remove noise in polyline without shrinkage. Please refer to the course slide of Dr. Tao Ju if you'd like to learn about Taubin smoothing method.[2]

There are 5 parameters in this step: *Lambda*, *Mu*, *Iterations*, *Threshold for Num of Turning Points*, and *Threshold for Num of Vertices*. The meaning and value range of these parameters are listed as follows.

- *Lambda*: How far each node is moved toward the average position of its neighbours during every second iteration. Type: Float. Range: $0 <$ *Lambda* < 1.
- *Mu*: How far each node is moved opposite the direction of the average position of its neighbours during every second iteration. Type: Float. Range: -1$<$ *Mu* < 0.
- *Iterations*: Number of iterations in Taubin smoothing. If you don't need polyline smoothing, set *Iterations* to 0. Type: Integer. Range: ≥ 0.

[2]CSE554 lecture slides

- *Threshold for Num of Turning Points*: Threshold value for the number of turning points in a polyline. Only those polylines with number of turning points greater than this threshold will be smoothed. Type: Integer. Range: ≥ 0.

- *Threshold for Num of Vertices*: Threshold value for the number of vertices in a polyline. Only those polylines with number of vertices greater than this threshold will be smoothed. Type: Integer. Range: ≥ 0.

Lambda, *Mu*, and *Iterations* are parameters for Taubin smoothing. There are two sets of parameter values you may use. I recommend Set 1 because Set 1 is much faster than Set 2 when the pristine boundaries contain a large number of vertices. Set 1 is the default value in Im2mesh_GUI.

- Set 1. *Lambda* = 0.7, *Mu* = -0.4, *Iterations* = 10.

- Set 2. *Lambda* = 0.5, *Mu* = -0.5, *Iterations* = 100.

In this step, there are two thresholds: *Threshold for Num of Turning Points*, and *Threshold for Num of Vertices*. These two parameters are introduced by me to avoid over-smoothing of simple polylines or polygons (Figure 4). Here, a turning point is defined as a vertex where the plane angle between two connected edges is not 180 degrees (Figure 5). By setting a threshold, those polylines with less turning points or less vertices will be skipped in this step so they will not be smoothed (Figure 6). If you want to perform smoothing to all the polylines, set the thresholds to 0.

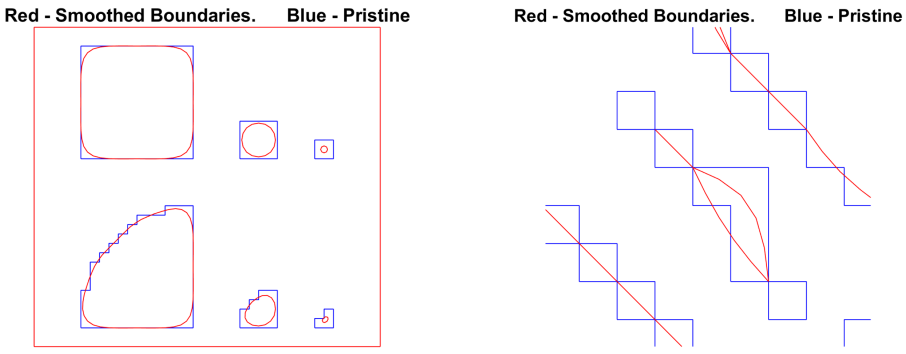


Figure 4: Examples of over-smoothing

Step 6. Simplify boundary. You can choose your input for this step by clicking the Switch. For example, if your input is from Step 5, just click the right side of the switch. This step uses Douglas-Peucker algorithm to simplify polylines. The subroutine (`dpsimplify.m`) is written by Wolfgang Schwanghart. There are 2 parameters in this step: *Tolerance*, and *Threshold for Num of Vertices*.

- *Tolerance*: The maximum allowable deviation of a vertex from the simplified curve. It's for Douglas-Peucker algorithm. Type: Float. Range: ≥ 0.

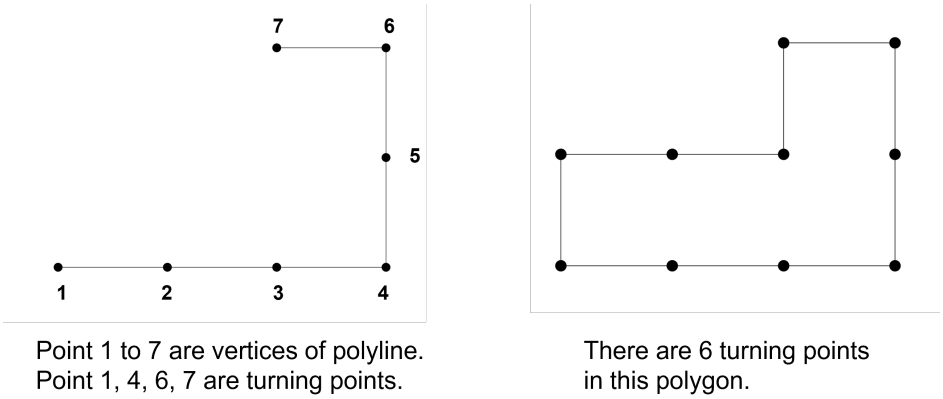


Figure 5: Examples of turning point

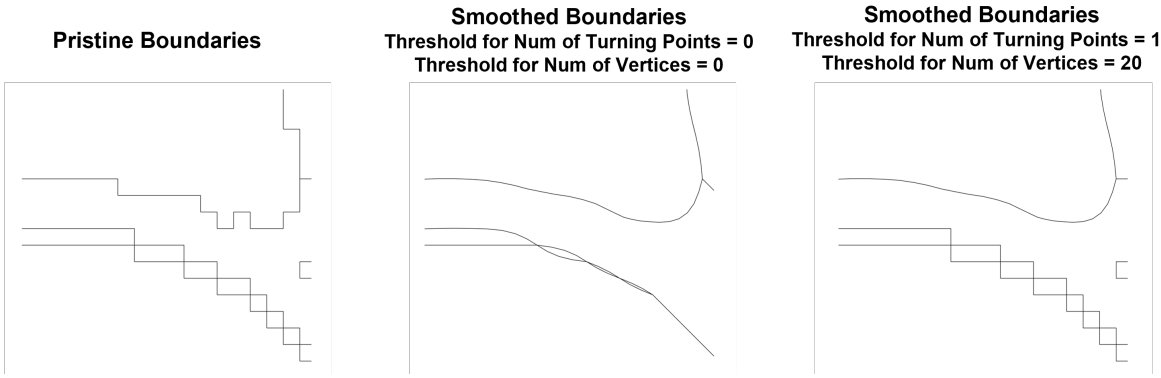


Figure 6: Set thresholds to avoid over-smoothing of simple polylines or polygons

• *Threshold for Num of Vertices*: Threshold value for the number of vertices in a polyline. Only those polylines with number of vertices greater than this threshold will be simplified. Type: Integer. Range: ≥ 0.

Higher *Tolerance* means fewer points are retained in polyline and worse approximation. If you don't need to simplify polylines, set *Tolerance* to 0. The reasonable value of *Tolerance* depends on your workflow and your image.

• When you're using the boundaries from Step 4 as input, the typical value of *Tolerance* is 0.8 - 2.

• When you're using the boundaries from Step 5 as input, the typical value of *Tolerance* is 0.2 - 0.8.

In this step, there is a parameter called *Threshold for Num of Vertices*. This parameter is used to avoid over-simplification of polyline. Figure 7 shows examples of over-simplification. Some of the over-simplified polygons even have zero area. By setting a threshold, those polylines with less vertices will be skipped in this step so they will not be simplified. If you want to perform simplification to all the polylines, set the threshold to 0.

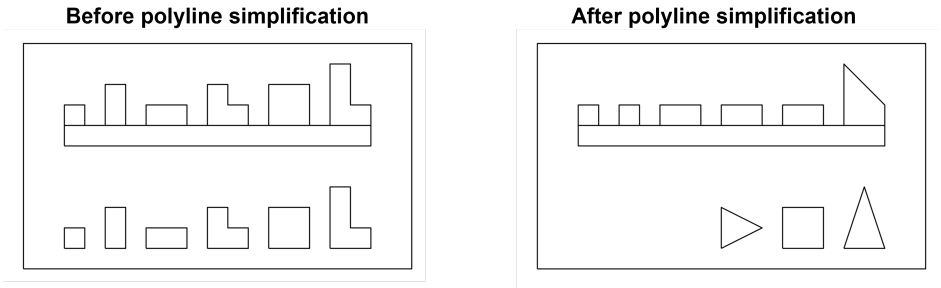


Figure 7: Example of over-simplification

Once you got the simplified boundaries. You can click button "View Boundary in New Window" or "Compare with Pristine Boundary" and zoom in to check the results. If the resulted boundary is not ideal, you can change parameters of Step 6 and click the button "Simplify" again to obtained new results.

Step 7. Select phase. All the phases are selected in the default case. If you don't need certain phases for meshing, un-check them in the table.

Step 8. Select mesh generator & meshing. There are two mesh generators available in Im2mesh: MESH2D and generateMesh.

MESH2D is a mesh generator developed by Darren Engwirda.[3] It's the default mesh generator of Im2mesh_GUI. It can generate high-quality finite element meshes. You are not required to install any MATLAB Toolbox when using MESH2D. There are 3 parameters for MESH2D: *Gradient-limit*, *Max Mesh-size*, and *Meshing Algorithm*.

- *Gradient-limit*: A limit on the gradient of mesh-size function (Figure 8).[4] Type: Float. Range: > 0. Typical value: 0.2 - 0.5.

- *Max Mesh-size*: Maximum mesh edge lengths. This is an approximate upper bound on the mesh edge lengths (Figure 9). Type: Float. Range: > 0.

- *Meshing Algorithm*: Method used to create mesh-size functions based on an estimate of the "local-feature-size" associated with a polygonal domain. Value: Delaunay-refinement or Frontal-Delaunay.

generateMesh is a MATLAB built-in function.[5] It requires installation of MATLAB Partial Differential Equation Toolbox. I developed a subroutine (`poly2meshBuiltIn.m`) to make the mesh generation for multi-parts become possible. There are 3 parameters for generateMesh: *Mesh Growth Rate*, *Max Mesh Edge Length*, and *Min Mesh Edge Length*.

- *Mesh Growth Rate*. The rate at which the mesh transitions between regions of different edge size. Type: Float. Range: $1 \leq$ *Mesh Growth Rate* ≤ 2. Typical value: 1.2 - 1.5.

[3] https://github.com/dengwirda/mesh2d

[4] http://persson.berkeley.edu/pub/persson04gradlim.pdf

[5] https://www.mathworks.com/help/pde/ug/pde.pdemodel.generatemesh.html

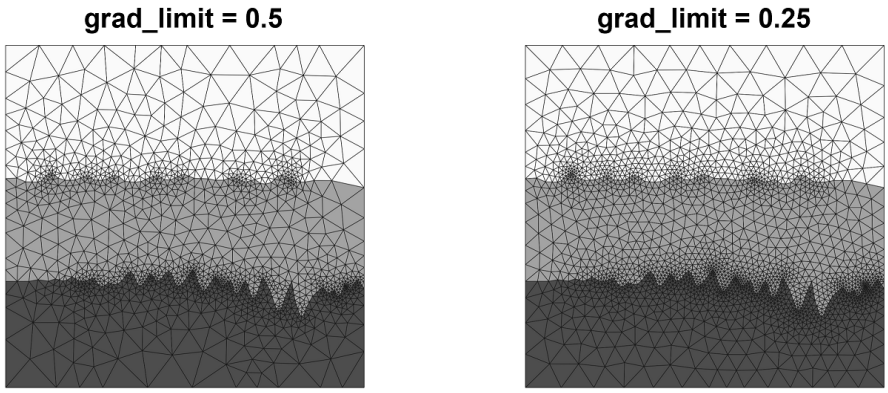


Figure 8: Effect of *Gradient-limit*

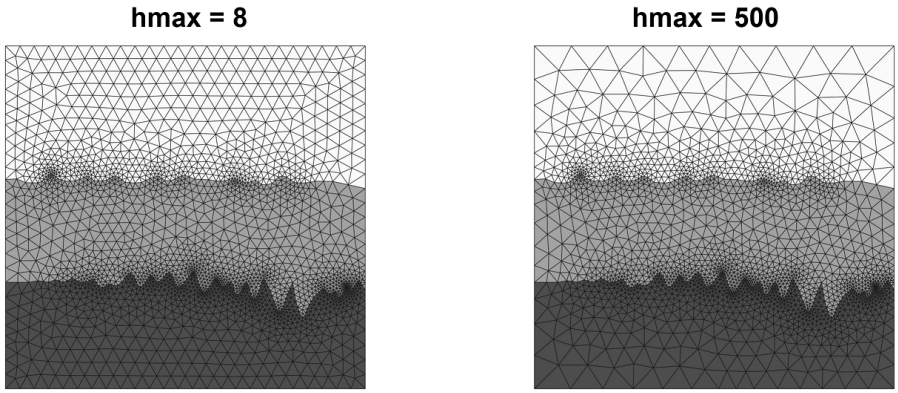


Figure 9: Effect of *Max Mesh-size*

• *Max Mesh Edge Length*: An approximate upper bound on the mesh edge lengths. Type: Float. Range: > 0.

• *Min Mesh Edge Length*: An approximate lower bound on the mesh edge lengths. Type: Float. Range: ≥ 0.

The step of meshing is the most time-consuming step in Im2mesh. The computation time of meshing is dependent on the number of vertices in the simplified boundaries. I ran tests on my desktop computer with 4-phase images and with option "Need to Avoid Sharp Corners?" = Yes. For 15,000 vertices in the simplified boundaries, MESH2D took 40-50 seconds. For 80,000 vertices in the simplified boundaries, MESH2D took 300-450 seconds.

What to do if the mesh generation has failed for your images?

• Set the option "Need to Avoid Sharp Corners?" to Yes, and re-run Step 4 to Step 8

• Set the thresholds in Step 5 or 6 to a higher value (e.g., 20), and re-run Step 5 to Step 8

Once you obtain the meshes from MESH2D or generateMesh. You can click button "View Mesh in New Window" or "Evaluate Mesh Quality" to check the results. "Evaluate

Mesh Quality" use a subroutine (`tricost.m`) written by Darren Engwirda to evaluate mesh quality. "Evaluate Mesh Quality" has 3 outputs (Figure 10). The definition of Q and θ are as follows.

- Q: Area-length measure of a triangle. $Q = \frac{4\,A}{\sqrt{3}\,l_{rms}^2}$, where A is the area of a triangle and l_{rms} is the root-mean-squared edge length in a triangle. Q achieve a score of 1 for ideal elements. Q approaches zero as an element distorts toward degeneracy.

- θ: The plane angle between adjacent edges.

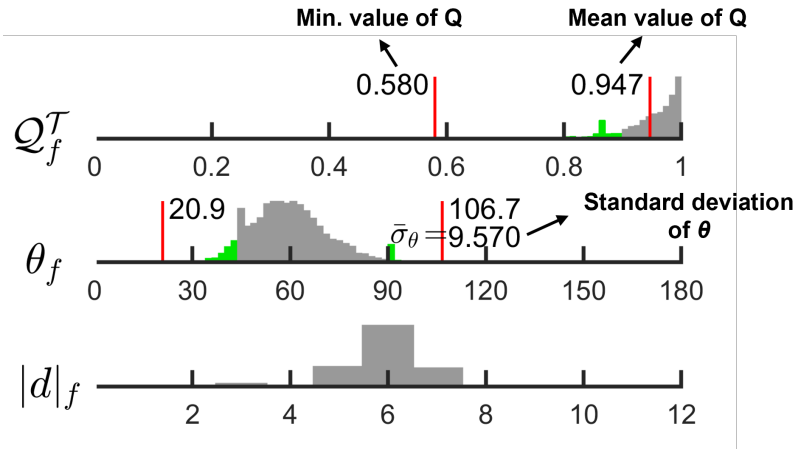


Figure 10: An example of mesh quality. A few statistics can be obtained from the plot.

If the resulted mesh is not ideal, you can change parameters of Step 8 and click the button "Meshing" again to obtained new results. You may also go back to Step 5 or 6 to change parameters. But once you do that, you need to re-run all the steps after Step 5 or 6 to get the updated results.

What are the critical parameters that affect the number of triangular meshes?

- *Tolerance* in Step 6.

- *Gradient-limit* in Step 8, if you are using MESH2D.

- *Mesh Growth Rate* and *Min Mesh Edge Length* in Step 8, if you are using generateMesh.

My suggestion for choosing the value of these critical parameters:

- First, try different *Tolerance* value in an ascending order and click button "Compare with Pristine Boundary" to view the corresponding simplified boundaries. Identify the largest *Tolerance* value that provides an acceptable approximation to the pristine boundaries. With a larger *Tolerance* value, the number of generated triangles in Step 8 will decrease.

- After that, try different *Gradient-limit* and check the corresponding mesh quality Q. You may perform a mesh convergence analysis to find the largest acceptable *Gradient-limit* for your cases.

Step 9. Export mesh. You can export mesh as `mat` file (MATLAB), `inp` file (Abaqus), and `bdf` file (Nastran bulk data, compatible with COMSOL).

The exported `mat` file contains 3 variables: *vertices*, *triangles*, and *phase_ code*.

- *vertices*: Node data. N-by-2 array.

  `vertices(i,1:2) = [x_coordinate, y_coordinate] of the i-th node.`

- *triangles*: Node numbering for each triangle. M-by-3 array.

  `triangles(j,1:3) = [node_numbering_of_3_nodes] of the j-th element.`

- *phase_ code*: Label of material phase. P-by-1 array.

  `phase_code(j,1) = k; means the j-th element belongs to the k-th phase.`

After loading the `mat` file into MATLAB, you can use the following commands to plot the meshes.

```
figure('color','white')
hold on; axis equal off;

label_unique = unique( phase_code );
num_phase = length( label_unique );

% setup color
if num_phase == 1
 col = 0.98;
elseif num_phase > 1
 col = 0.3: 0.68/(num_phase-1): 0.98;
else
 error("num_phase < 1")
end

for i = 1: num_phase
 current_phase = label_unique(i);
 patch(...
 'faces',triangles( phase_code==current_phase, 1:3 ), ...
 'vertices',vertices, ...
 'facecolor',[ col(i), col(i), col(i) ], ...
 'edgecolor',[.1,.1,.1] ...
 );
end
hold off
```

Before exporting `inp` file and `bdf` file, you need to setup some parameters, such as *dx*, *dy*, and *Element Type*.

dx and *dy* are the scales of a pixel. *dx* is the column direction, and *dy* is the row direction. In most cases, *dx* and *dy* are equal. The value of *dx* and *dy* depends on the scale of your image and the unit in your finite element simulation. For example, the scale of your image is 0.11 mm/pixel, you can set $dx = 0.11$ and $dy = 0.11$.

When exporting `inp` file, there are 2 options:

- A model with multiple parts. Each phase corresponds to one part in Abaqus.
- A model with one part, which contains multiple sections. Each phase corresponds to one section in Abaqus.

Im2mesh-GUI currently only support exporting linear element.