Local-Global Image Binarization for Reconstructing the Cellular Structure of Polymer Foam Materials

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ABSTRACT

This paper presents a new hybrid method for the adaptive binarization of cellular structures in the computer aided modeling of polymer foam materials. The proposed method incorporates two established binarization methods, one global approach and one local. The binarization of cellular structures presents particular challenges as images often include distinctive edges that exist at different depths. This issue is addressed along with the common problems of noise and gradients that can be present in images. By incorporating global information with the local information, the current method was able to maintain the details achieved by the local method while reducing the noise as a global method does. Experimental results indicate the efficacy of our approach in comparison with existing methods. The proposed method can be applied in bio-inspired material design, bio-medical materials, and polymer materials science in general.

Keywords: reverse engineering, cellular structure, engineering materials, image binarization, reconstruction.
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1 INTRODUCTION

Computer aided modeling of polymer foam materials is an important tool for bio-inspired material design and bio-medical materials. The modeling also provides vital information for the computer aided analysis of polymer cellular materials in general. Unfortunately, the wall thickness of cellular structures of many polymer foam materials is about 10 micrometers, while most of micro-focus X-ray computed tomography (XCT) systems have a resolution between 7 to 10 micrometers. It is a serious challenge how to accurately reconstruct the cellular structures of these foam materials with the existing XCT systems.

Image binarization of XCT data is the first step in the reconstruction of digital models for polymer foam materials. It is also a useful process with applications in optical character recognition (OCR) [1], and the study of cellular structures [2]. The process usually involves comparing each pixel to some calculated threshold value, with the output consisting of a background and foreground objects. Binarization techniques are generally divided into two categories: the global approaches and the local approaches. There are benefits and drawbacks to each approach (Fig. 1). In this figure, highlighted in red in the Otsu output (a global method) are edges that were missed [3], while the local method [4] generated noise around the perimeter of the image, as well as in cavities of the polymer foam cell walls.

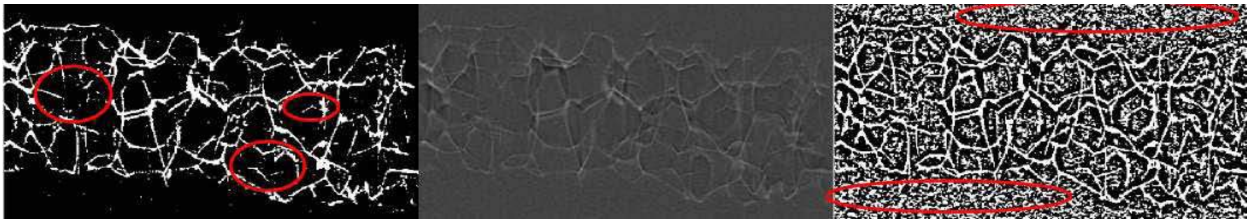


Fig. 1: Drawbacks of Existing Methods (From left to right: Otsu's method (global), original image, Niblack's method (local) with a search window radius of 15 pixels).

The global approaches try to find an optimal thresholding value for the entire image. These approaches are good for simple images, and typically have a lower computational complexity compared to the local methods. The global approaches have difficulty, however, when an image contains increasing amounts of degradation and varying luminosities [5]. Adaptive local thresholding has been shown to better handle images that contain variable illumination (Sauvola & PietikaKinen, 2000) [6]. The drawback of many of the local methods is that the thresholding tends to generate a significant amount of noise [5].

The current study aims to find a hybrid approach that can accurately threshold lower resolution images obtained from X-ray computed tomography. Some of the more prevalent global and local methods are examined to see which algorithms show the most promise in evaluating our test cases. These methods are then combined to see if a hybrid approach can better evaluate the binarization of fuzzy cell images over the global or local approaches.

The remaining of this paper is organized as follows. In Section 2, the algorithmic description of a new hybrid approach of image binarization is introduced. Then, experimental setup and result are given in Section 3. Next in Section 4, discussion on the experimental results is provided and comparison is conducted against existing methods. Finally, some concluding remarks are provided in Section 5.

2 METHODOLOGY

The overall strategy of this study is (1) to find the best local method and the best global scheme among existing approaches in the cases of polymer foam materials, and (2) to explore a way to combine these two methods to form a new hybrid approach.

2.1 Test Cases

The test cases used in this study are foam images that were obtained using an X-ray computed tomography system. The resolution of the machine is 10 micrometers. The test cases showcase distinct cell walls at multiple depths. The current study is primarily concerned with having the ability to detect all distinctive features at multiple depths, with a secondary desire of being able to identify the uppermost cellular structures.

2.2 Algorithm Selection

Our test cases first underwent binarization by way of a variety of global and local thresholding methods. This was done using ImageJ (http://rsb.info.nih.gov/ij/), an open-source image processing program. Each algorithm was coded by Landini [7] and implemented as a plugin for the ImageJ software. Global methods tested included Huang and Wang's fuzzy thresholding method [8], Li and Tam's Minimum Cross Entropy thresholding [9], Otsu's method [3], and Yen et. al.'s multilevel thresholding [10]. The local methods explored were the Niblack [4] and Bernsen [11] algorithms. From these results we selected the single best global and the single best local algorithm to be utilized in the hybrid approach. By inspection it was determined that Niblack's local method captured the most cell walls among the local approaches, while Huang's global approach captured the most cell walls while containing minimal noise across all test cases.

2.3 Hybrid Implementation

In order to utilize the information from both the Huang and Niblack methods, we first obtain the binarization results from both methods. In order to determine the best method to use for deciding on whether a given pixel is part of a cell wall or part of the background, we use the standard deviation of the gray levels in the images:

$$B_m = \begin{cases} B_n, & if\ |B_n - B_h| > 2\sigma \\ B_h, & otherwise \end{cases}, \tag{1}$$

where B_n and B_h represent the pixel binarization produced by the Niblack and Huang methods, respectively. B_m is the pixel binarization of our hybrid method. σ refers to the standard deviation of image gray levels.

We decided upon this determination due to the potential presence of large gradients or varied luminosities in a given image. In cases where there is a large variance in the gray levels in an image, local methodologies tend to perform well, whereas global approaches tend to calculate large portions of the given image to be a part of the background. Using this knowledge, we decided to utilize the absolute value of the difference of the Huang and Niblack results as a heuristic for determining whether the pixel under evaluation may exist in an area of the image with a gradient. If the difference is large, it is likely that the given pixel exists within a gradient, indicating the Niblack result would be the better evaluation criteria for that pixel.

A natural question that arises is what constitutes a large difference for the B_m selection, as the range of the gray levels varies between images. It was determined through inspection that using twice the standard deviation for the entire image as the difference threshold provided the best results across multiple test cases. While better results can be obtained on any given image by manually selecting a difference threshold, using twice the global standard deviation provided a generalized approach that works well across multiple test cases. Using the global measure of standard deviation also provided better results across test cases than using the local measures of variance and standard deviation calculated from the evaluation windows used in the Niblack method.

Overall, the procedure of our hybrid method can be illustrated by a flow chart in Fig. 2. The program starts from the left end of this figure and complete at the right end.

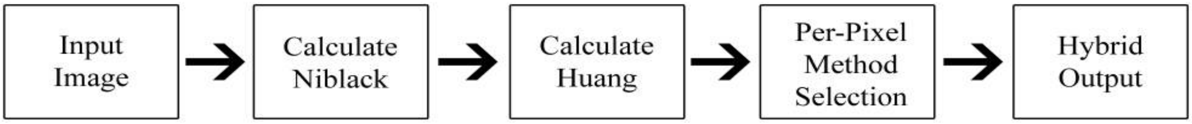


Fig. 2: Image processing flow chart.

2.4 Model Parameters

As the proposed hybrid method utilizes Niblack's local approach, it also inherits its parameters. Niblack's method determines whether a pixel is part of an object or part of the background by using the local mean, local standard deviation, and constant k (k = 0.2 for light images and -0.2 for dark images):

$$\text{Pixel} = \begin{cases} \text{Object}, & if\ pixel\ value > ((local\ mean) + k \times (local\ \sigma)) \\ \text{Background}, & otherwise \end{cases}, \tag{2}$$

where Pixel refers to the binarization value given to a particular pixel. If the pixel is part of an object, it is given the value of 255. Otherwise, the pixel is deemed part of the background and given a value of 0.

In regards to the proposed hybrid method, this means there are two parameters the user can set: *k* and the size of the evaluation window. For this experiment, *k* was held constant at 0.2, though it has been shown that pre-calculating *k* provides more accurate results (Yan et. al., 2005) [12]. The size of the evaluation window was held constant at 15 pixels for the hybrid method as well as both local approaches evaluated in the current study.

3 EXPERIMENT AND RESULTS

3.1 Experimental Setup

For the accurate measurement of cellular structures of foam materials, a high-resolution micro-focus X-ray computed tomography system (XCT) was used to measure voids and cracks in material specimens (Fig. 3a). It was manufactured by Phoenix X-ray Company. The maximum power and voltage of X-ray tube are 320 W and 225 KeV, respectively. Figure 3b is an example of polymer foam specimen used in this study.

(a) XCT system

(b) Foam specimen

Fig. 3: Micro-focus X-ray computed system and a polymer foam specimen.

3.2 Construction of Ground Truth Images

In order to evaluate the accuracy of each algorithm, a ground truth image was constructed for each test case. A number of factors were taken into consideration when constructing the ground truth images. As our main objective was to capture as many cell walls as possible, the cell walls captured at varying depths in a given image were defined as objects in the ground truth image. We also focused on making sure the ground truth images did not complete edges that were not captured in a given image, as the goal of the binarization was to evaluate the existing pixels rather than to extrapolate cellular structures the imaging equipment may have failed to capture at a high enough resolution.

3.3 Results

In general, the global binarization methods outperformed the local methods for most of our test cases. As summarized in Table 1, the only instance where a local method held a higher percent correct value was the Niblack method for the foam2 (Fig. 5) test case. This is perhaps expected given the foam1 (Fig.

4), foam3 (Fig. 6), and foam4 (Fig. 7) test cases have a similar composition with cell walls being generally further apart than for the foam2 test case. The percent correct values for the Niblack and Bernsen approaches were higher than all but the Huang result, suggesting the binarization of foam2's densely packed cells benefited from the small evaluation windows used in the local approach.

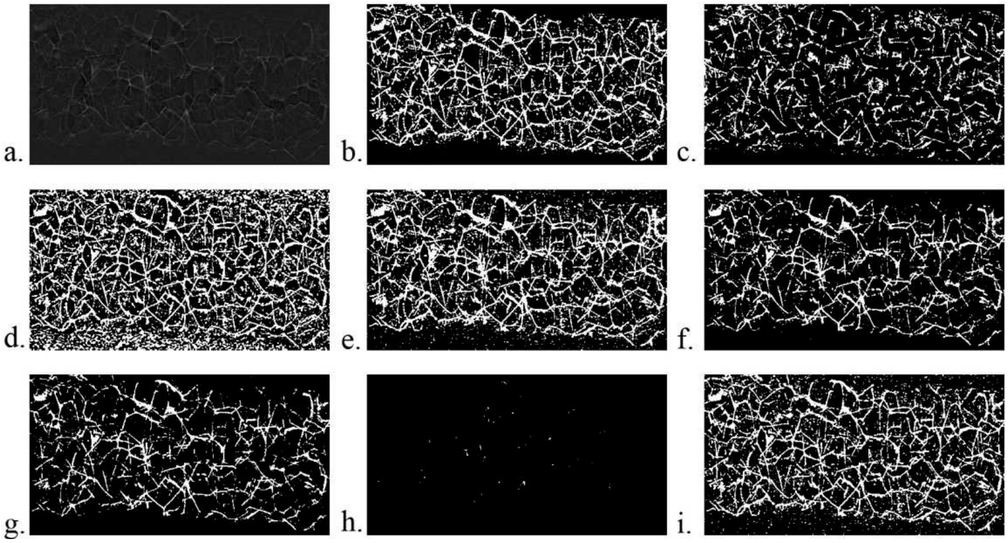


Fig. 4: Binarization results for Foam1 test case: (a) original image (b) ground truth image (c) Bernsen (d) Niblack (e) Huang (f) Li (g) Otsu (h) Yen (i) Hybrid.

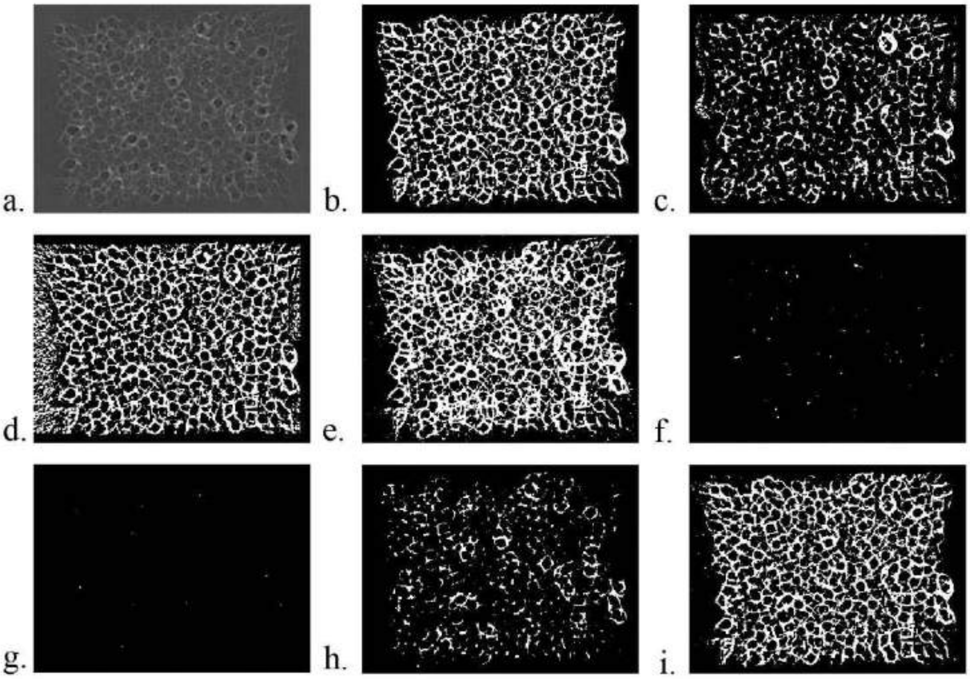
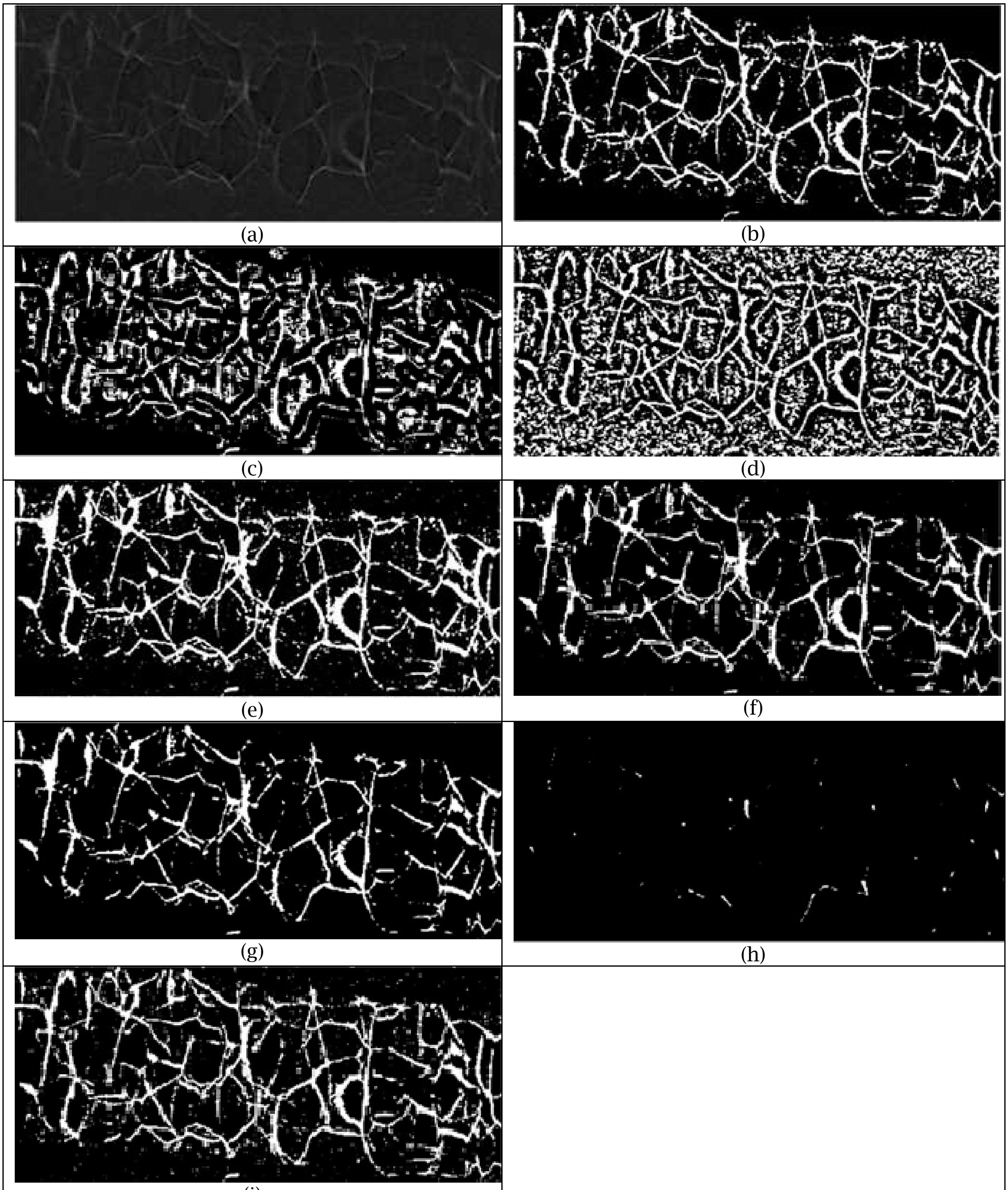


Fig. 5: Binarization results for Foam2 test case: (a) original image (b) ground truth image (c) Bernsen (d) Niblack (e) Huang (f) Li (g) Otsu (h) Yen (i) Hybrid.



(a) (b) (c) (d) (e) (f) (g) (h) (i)

Fig. 6: Binarization results for Foam3 test case: (a) original image (b) ground truth image (c) Bernsen (d) Niblack (e) Huang (f) Li (g) Otsu (h) Yen (i) Hybrid.

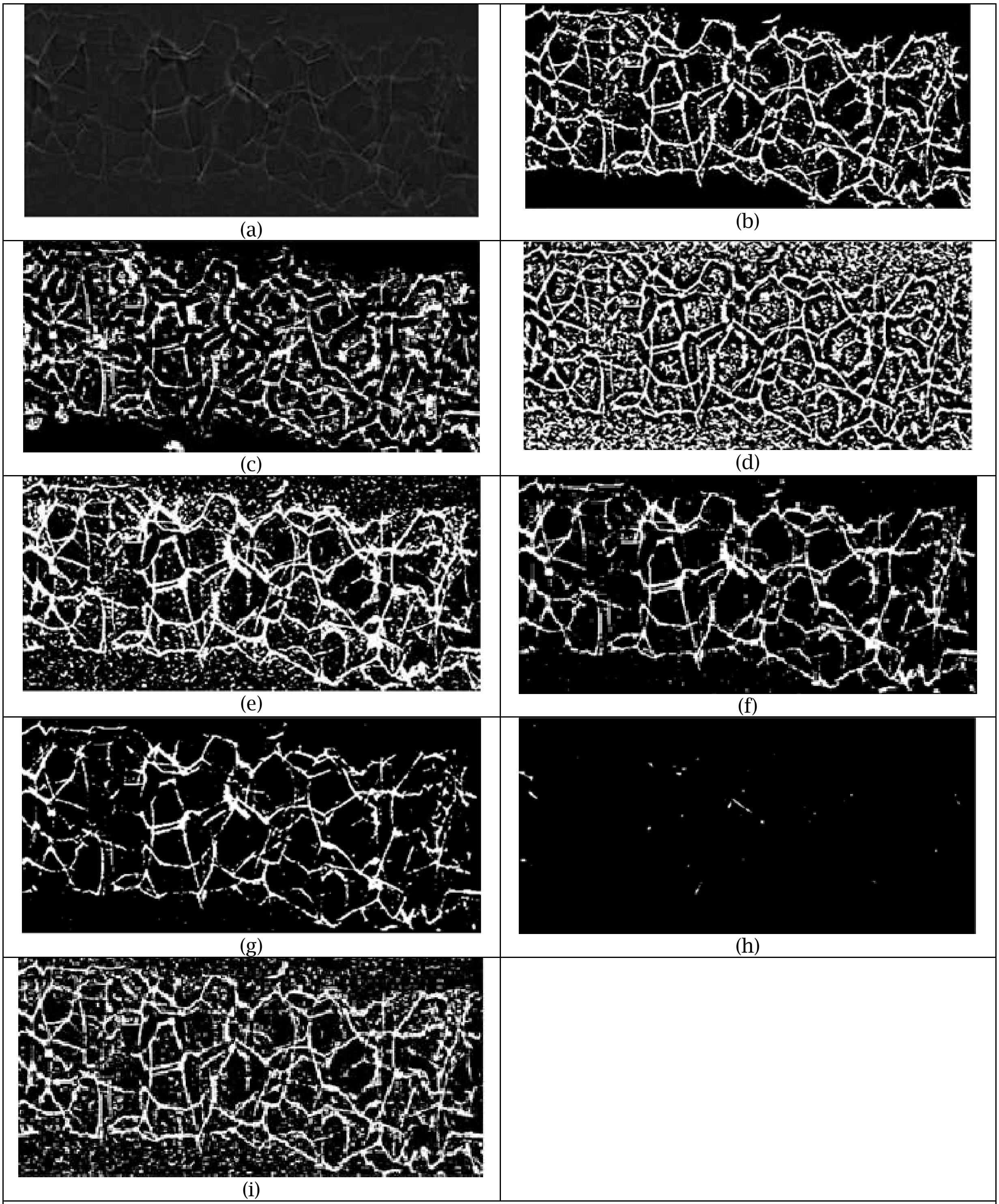


Fig. 7: Binarization results for Foam4 test case: (a) original image (b) ground truth image (c) Bernsen (d) Niblack (e) Huang (f) Li (g) Otsu (h) Yen (i) Hybrid.

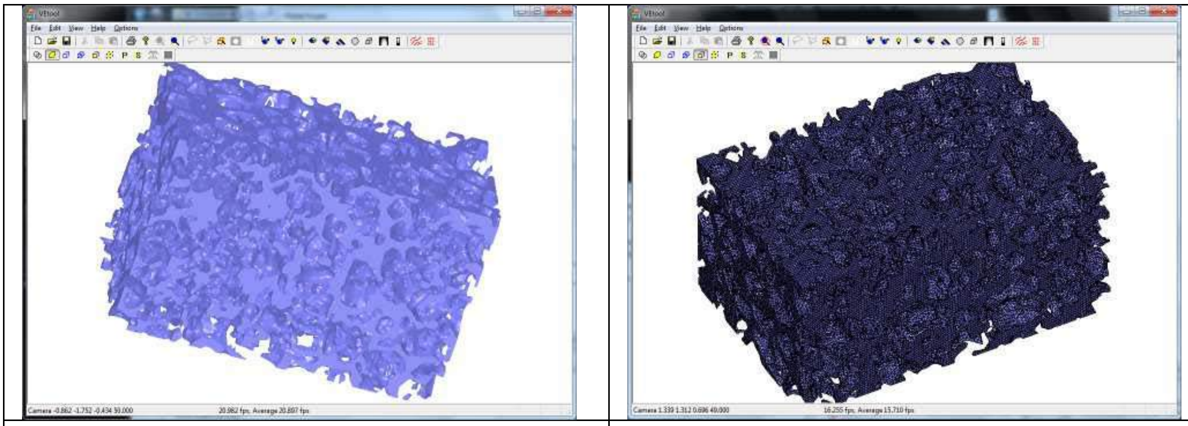
Test Case	Total Pixels	Global Methods				Local Methods		Hybrid
		Huang	**Li**	**Otsu**	**Yen**	**Bernsen**	**Niblack**	
Foam 1	133233	97.24	97.24	90.27	78.13	86.08	88.90	99.25
Foam 2	128544	92.89	74.75	74.60	80.78	85.53	94.89	99.70
Foam 3	247450	92.94	91.95	90.41	79.64	87.94	85.42	97.18
Foam 4	221998	97.74	95.46	94.23	84.56	88.75	80.62	99.63
Mean	-	95.20	89.85	87.37	80.78	87.08	87.46	98.94
Standard Deviation	-	2.65	10.30	8.71	2.75	1.52	6.01	1.19

Tab. 1: Percent Correct.

4 DISCUSSION

In this study we combined Huang and Wang's object attribute based model of minimizing measures of fuzziness with Niblack's local adaptive thresholding method. This hybrid approach generated more accurate binarization results across every test case than any other algorithm tested. One description of the hybrid method's performance is that it tends to thin the edges found from the Huang and Wang result while adding some cell walls that the Niblack method was able to detect over the Huang and Wang method.

The results are not perfect, as the hybrid approach still generates noise around the perimeter of most of our test cases. As with the Niblack and Bernsen methods, there are parameters that the user must give the hybrid approach such as the size of the evaluation window and the *k* value. Though it was held constant for this experiment, the global standard deviation used in the algorithm switching function can be changed to produce better results for different test cases. Using double the global standard deviation was a solution that tended to provide the best results across various test cases. By adding this parameter to the window size and the *k* value, the proposed hybrid method becomes more complex and perhaps difficult for a user to tune to their specific test case.



(a) Surface CAD models

(b) Volumetric finite elements

Fig. 8: Reconstructed 3D models of polymetric foam materials.

The result of image binarization is then used as an input to the surface reconstruction through many existing algorithms such as marching cube method [13], leading to a surface CAD model in the format of polygonal mesh. Figure 8 demonstrates a CAD model via our in-house visualization code, MCAD. Wave front method [14] is a reliable volume meshing scheme that is used to generate finite elements within the domain of polymeric foams. Based on the finite element models, thermal, electrical and mechanical analyses can be conducted to evaluate the performance of the measured polymeric foams. Design optimization is enabled by investigating a series of polymeric foams with different cell sizes. Digital diagnosis of material damage in polymeric foams becomes possible through the visualization of the reconstructed CAD models and numerical analyses based on damage and fracture mechanics.

5 CONCLUSIONS

Overall, the hybrid approach in the current study provides one more method for the binarization of cellular structure images. The method has shown promise in the binarization of lower resolution, hazy images for the accurate reconstruction of cellular structures of polymer foam materials via micro-focus X-ray computed tomography technology. Experiment results indicate that the accuracy of our approach is remarkably better than that of existing methods in the test cases of polymer foam materials. It leaves open the possibility of future refinement through the inclusion of edge detectors and entropy-based models. The outcome of our method can be used to reconstruct a CAD model of polymeric foams for visualization and subsequent computer aided analyses.

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