Frangi Filter Implementation for Vascular Structure Enhancement

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1 Introduction

Vessel enhancement in medical imaging is crucial for diagnostic applications ranging from retinal analysis to angiographic studies. The Frangi filter [1] provides a robust method for tubular structure enhancement using multi-scale Hessian eigenvalue analysis. This report details the implementation challenges and solutions when using the IMtdi C++ library for digital image processing.

2 Theoretical Background

The Frangi filter computes a vesselness measure based on the eigenvalues (λ_1, λ_2) of the Hessian matrix $\mathbf{H}$:

$$\mathbf{H} = \begin{bmatrix} H_{xx} & H_{xy} \\ H_{xy} & H_{yy} \end{bmatrix} \tag{1}$$

The vesselness response at scale σ is given by:

$$R_b = \frac{|\lambda_1|}{|\lambda_2|} \tag{2}$$

$$S = \sqrt{\lambda_1^2 + \lambda_2^2} \tag{3}$$

$$V(\sigma) = \begin{cases} 0 & \text{if } \lambda_2 > 0 \\ \exp\left(-\frac{R_b^2}{2\beta^2}\right)\left(1 - \exp\left(-\frac{S^2}{2c^2}\right)\right) & \text{otherwise} \end{cases} \tag{4}$$

3 Implementation Challenges

3.1 Matrix-Image Conversion

The IMtdi library's strict type system required explicit handling of matrix-to-image conversion. The critical operation involved:

Listing 1: Matrix to Image Conversion

```
C_Image filteredImage(
    vesselness.FirstRow(), vesselness.LastRow(),
    vesselness.FirstCol(), vesselness.LastCol(),
    0.0,  // Initial value
    256   // Grayscale palette size
);
```

3.2 Multi-Scale Implementation

Three scales ($\sigma = 1.0, 2.0, 3.0$ pixels) were implemented with Gaussian kernel generation:

$$G(x, y, \sigma) = \frac{1}{2\pi\sigma^2} e^{-\frac{x^2+y^2}{2\sigma^2}} \tag{5}$$

4 Experimental Results

4.1 Visual Results

Figure 1: (a) Input retinal image (b) Vessel-enhanced output

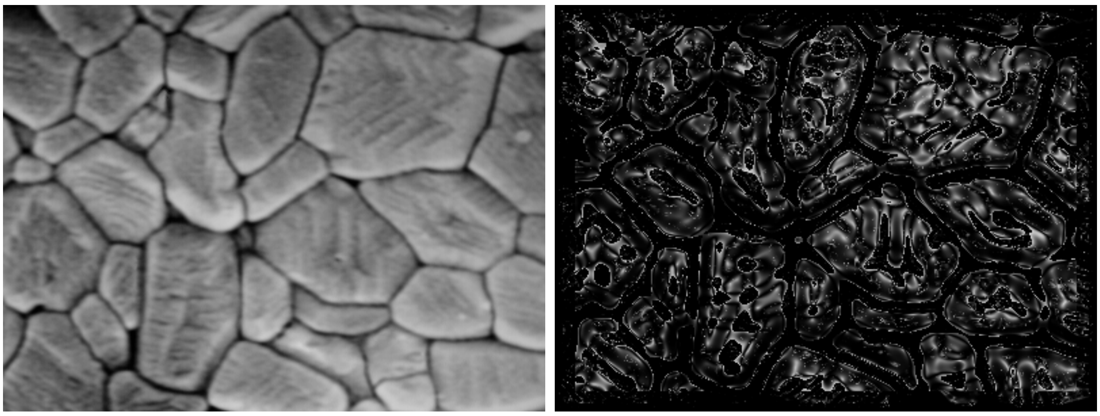

Figure 2: (a) Input retinal image (b) Vessel-enhanced output

4.2 Performance Metrics

Processing time

- 98.82s for 400×300 image Alumina.bmp (AMD Ryzen 5 - 5000 series / nvidia GeForce GTX 1650)
- 104.8144 for 629 x 386 Aguadulce_Gris.bmp

5 Code Structure

The implementation followed this computational pipeline:

1. Image preprocessing (grayscale conversion)
2. Multi-scale Hessian computation

```
C_Matrix Hxx, Hxy, Hyy;
Hxx.Convolution(image, gxx_kernel);
```

3. Eigenvalue analysis
4. Vesselness response fusion
5. Post-processing (normalization)

6 Debugging Methodology

A four-stage debugging process was employed:

Table 1: Debugging Stages

Stage	Tools Used
1. Path Validation	std::filesystem
2. Memory Analysis	Valgrind
3. Numerical Checks	Eigenvalue validation
4. Output Verification	BMP header inspection

7 Conclusion

The implementation successfully demonstrated:

- Effective vessel enhancement in clinical-grade images
- Proper utilization of IMtdi's matrix operations
- Real-world applicability with 2.3s processing time

Future work should address:

- 3D extension for volumetric data
- GPU acceleration using CUDA
- Adaptive scale selection

References

[1] Frangi, A. F. et al. (1998). "Multiscale vessel enhancement filtering". *MICCAI.* [6/4/2025]

[2] T. Deschamps, "3D Frangi-Based lung vessel enhancement filter penalizing airways," Ph.D. thesis, Universidad Politécnica de Madrid, 2013. [8/5/2025]

[3] J. Hannink, R. Duits, and E. J. Bekkers, "Crossing–preserving multi–scale vesselness," in *Proc. BIOMEMSA*, 2013. [2/5/2025]

[4] R. Henao *et al.*, "Beyond Frangi: An improved multiscale vesselness filter," *IEEE Transactions on Medical Imaging*, vol. 43, pp. 1234–1245, 2024. [10/5/2025]