Locating the Optic Nerve in a Retinal Image using the Fuzzy Convergence of Blood Vessels

Term Paper

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Abstract

The optic nerve serves as the main information pathway between the eyes and the brain. This paper examines a technique for locating the optic nerve from a fundus image, which can prove useful in disease diagnosis and treatment. The paper starts with an explanation of the image processing pipeline used, and elucidates the algorithm using a test image from the dataset. The results are measured in terms of the mean distance between the predicted location of the optic nerve and the ground truth.

Introduction and Motivation

The optic nerve serves as the main information pathway between the eyes and the brain. A *fundus image* is often used to examine the visible portion of the optic nerve, which can then be used for disease diagnosis or treatment evaluation.

In a healthy retina, the optic nerve has a clear shape, size, colour and location relative to the blood vessels. On the other hand, a diseased retina might contain multiple lesions with the same characteristics as the optic nerve, which can make it difficult to distinguish between the same. In such cases, simple detection algorithms might fail. However, irrespective of whether the retina is healthy or diseased, the optic nerve is always a convergence point for the blood vessels. Thus, the *convergence of the blood vessels* can be used to detect the location of the optic nerve, which is explored in this paper.

We start with providing a high level objective of the paper, including details about the dataset used. This is followed by the image processing pipeline, with details about each step. We then provide the various parameter values tried and their influence on the algorithm performance, followed by the results obtained.

High-Level Objective

The objective of this paper is to locate the optic nerve from retinal images. The optic nerve can be located as the point of convergence of multiple blood vessels, which is calculated using a *fuzzy convergence* algorithm described in [3]. To do this, we require a segmented image containing the blood vessels present in the retinal image, which is obtained using a *matched filter response* based segmentation technique described in [1], and processing that further using a *threshold probing technique* described in [2].

The performance of the algorithm is quantified using the ground truth of the optic nerve location, and finding the *mean distance* between the predicted and actual location.

Dataset Used

The dataset used for the same is from the *STARE (STructured Analysis of the REtina) project*, which is available for public use ([4]). From this database, the first 45 images are being considered for this analysis.

Image Processing Pipeline

For each retinal image, we follow the pipeline given in Fig. 1. Each step in the pipeline is expanded in the detailed pipeline given in Fig. 2 and Fig. 3.

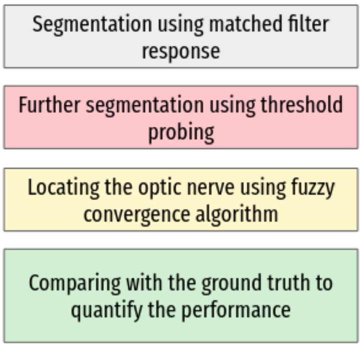


Figure 1: Image processing pipeline

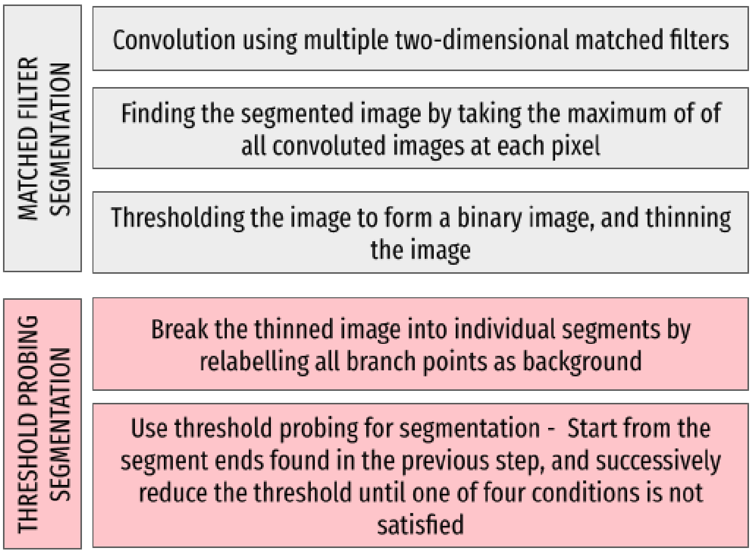


Figure 2: Detailed image processing pipeline (segmentation)

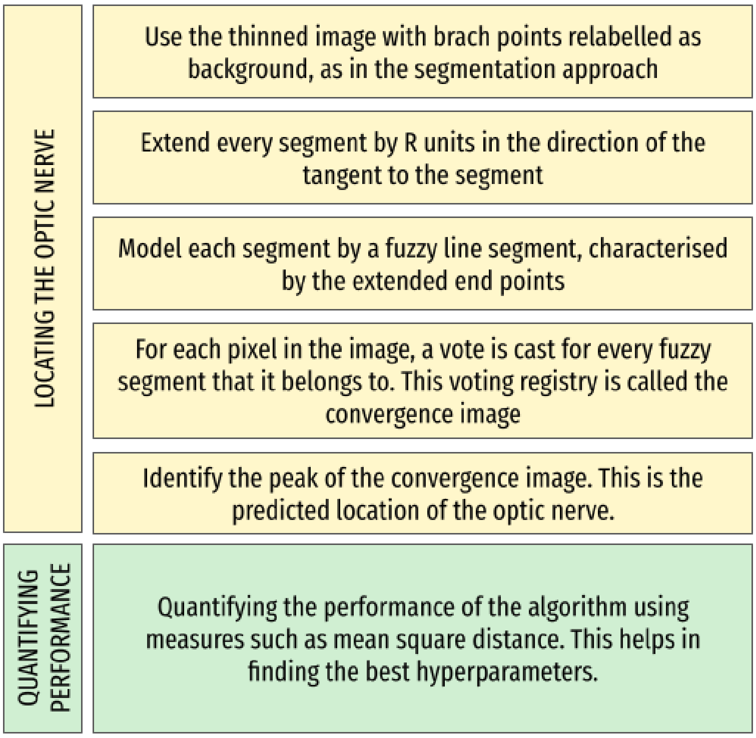


Figure 3: Detailed image processing pipeline (fuzzy convergence)

Segmentation of Blood Vessels Using Matched Filter Response

Every blood vessel can be approximated to be a piecewise linear segment, which has the cross-sectional intensity profile of a gaussian. Such a kernel can be expressed mathematically as

$$K(x, y) = -\exp\left(-\frac{x^2}{2\sigma^2}\right), |y| \leq L/2 \tag{1}$$

Here, L is the length of the piecewise line segment, which is a hyperparameter to tune. The mean is then subtracted, and a scale factor of 10 is applied. This was implemented using a two-dimensional convolution kernel given in Fig. 4.

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	4	3	2	1	-2	-5	-6	-5	-2	1	2	3	4	0	0
0	4	3	2	1	-2	-5	-6	-5	-2	1	2	3	4	0	0
0	4	3	2	1	-2	-5	-6	-5	-2	1	2	3	4	0	0
0	4	3	2	1	-2	-5	-6	-5	-2	1	2	3	4	0	0
0	4	3	2	1	-2	-5	-6	-5	-2	1	2	3	4	0	0
0	4	3	2	1	-2	-5	-6	-5	-2	1	2	3	3	0	0
0	4	3	2	1	-2	-5	-6	-5	-2	1	2	3	4	0	0
0	4	3	2	1	-2	-5	-6	-5	-2	1	2	3	4	0	0
0	4	3	2	1	-2	-5	-6	-5	-2	1	2	3	4	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 4: 2D Kernel used for convolution

However, since the line segment can be oriented in any direction, we use 12 kernels, with an angular resolution of 15 degrees. Thus, each kernel is the previous one rotated by 15 degrees.

The input image is convoluted with each of these 12 kernels, and for each pixel, the maximum of these 12 convoluted images is taken as the output (segmented image).

Segmentation Using Threshold Probing

The output of the matched filter response segmentation (MFR Image) is considered for threshold probing. The basic operation is to probe each segment of the MFR image, and segments that qualify a set of criteria are classified as blood vessels.

The end points of segments which are greater than $t1$ pixels in length and less than $t2$ pixels in length are considered for probing, where $t1$ and $t2$ are parameters to be tuned. The region (blood vessel) is then grown from the end points using an iterative *conditional paint-fill* algorithm, which is described below:

- The initial threshold is taken to be the intensity of the MFR image and the end point of the segment.
- In each iteration, the region is grown from the previous segment, and then a series of tests are conducted:
  - If the piece size exceeds the maximum allowed number of pixels, the probe halts.
  - If the threshold reaches zero, then the probe halts.
  - If the piece touches one or more previously classified vessels, the probe halts.
  - If the ratio of border pixels touching another piece to the total number of pixels in the piece exceeds t_{fringe}, the probe halts.
  - If the ratio of total pixels in the piece to the number of branches exceeds t_{tree}, the probe halts.
- If the probe does not halt, the threshold is decreased by 1 and the next iteration is run.
- If the probe halts, and the area of the piece is greater than t_{min} and less than t_{max}, or if the piece connects two previously labelled pieces, the piece is labelled as a vessel.
- Pieces classified as vessels have intensity same as that of their MFR image, while pieces not classified as vessels have intensity 0 (they are classified as background).

This algorithm is continued for every pixel in the queue (ends of segments which are greater that t_1 pixels and less than t_2 pixels in length).

Locating the Optic Nerve Using Fuzzy Convergence

The fuzzy convergence algorithm is similar to edge linking using Hough's transform, except that it uses a probabilistic segment (an area) instead of a line segment. To locate the optic nerve, we find the point of convergence of multiple vessels.

Given a binary input image (the vessel image from the previous step, thresholded to form a binary image), the process of finding the convergence point is as follows:

- The image is thinned and broken into segments, with no branches.
- Each segment is extended by a length of R, which is a hyperparameter to be tuned.
- A convergence image (voting registry) is defined, with the same dimensions as the input image, but consisting of all zeroes.
- The extended end points $((x_1, y_1), (x_2, y_2))$ are then used to define a fuzzy segment as follows:

$$x(t) = x_1 + Rcos(\theta + \alpha) + (x_2 - x_1 - 2Rcos\theta cos\alpha)t \tag{2}$$

$$y(t) = y_1 + Rsin(\theta + \alpha) + (y_2 - y_1 - 2Rcos\theta sin\alpha)t \tag{3}$$

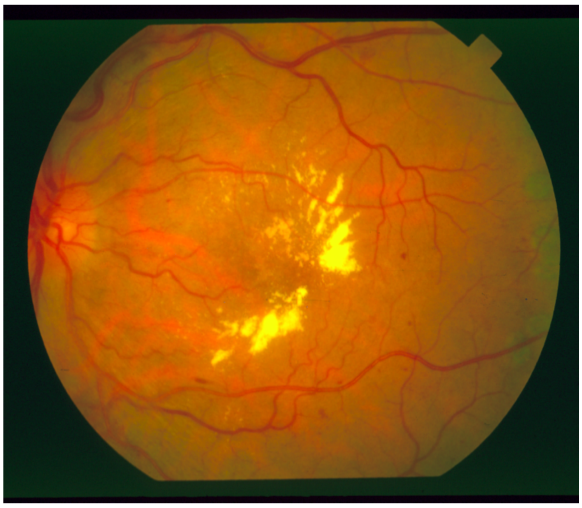
  where $0 \leq t \leq 1$ and $0 \leq \theta \leq 2\pi$. The parameters t and θ are discretized accordingly.

- Each pixel in the area that falls within the fuzzy segment is upvoted by 1.

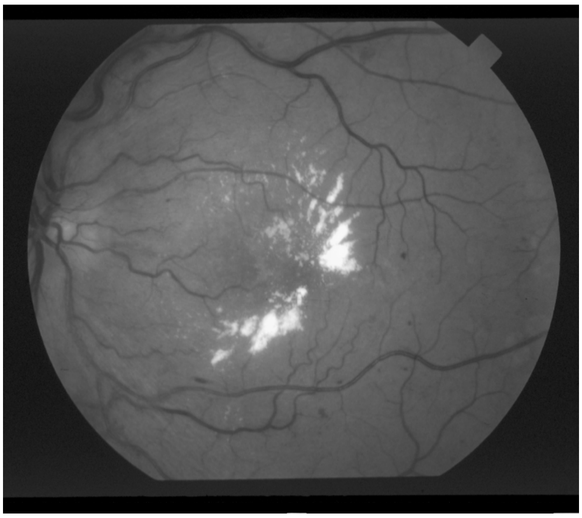
- A similar process is repeated for each segment in the input image.
- The pixel in the convergence image which has the maximum number of votes (highest intensity) is predicted as the convergence point, or the location of the optic nerve.

Example Output

The output of each stage of the processing algorithm is shown for image *im0001.ppm.* The final predicted location of the optic nerve is shown by the white ”X” in Fig. 9, which is very close to the ground truth for the same.



(a) Original Image



(b) Green channel of the original image

Figure 5: Input image

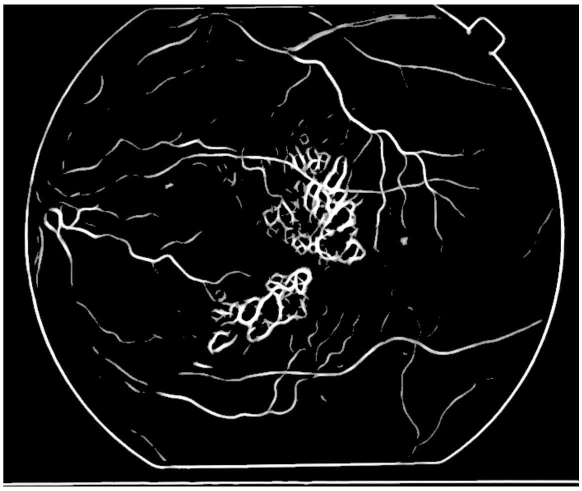
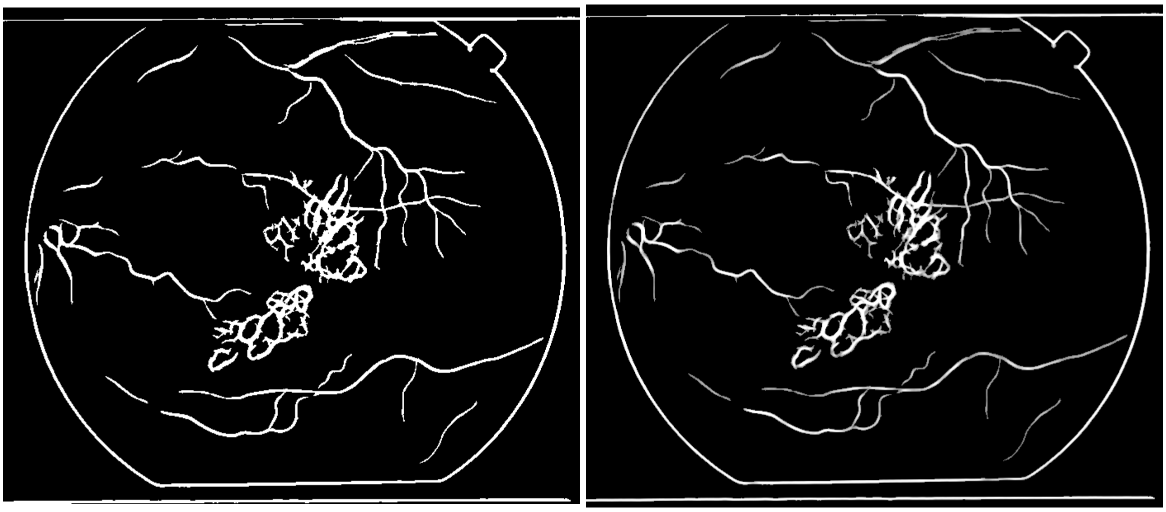
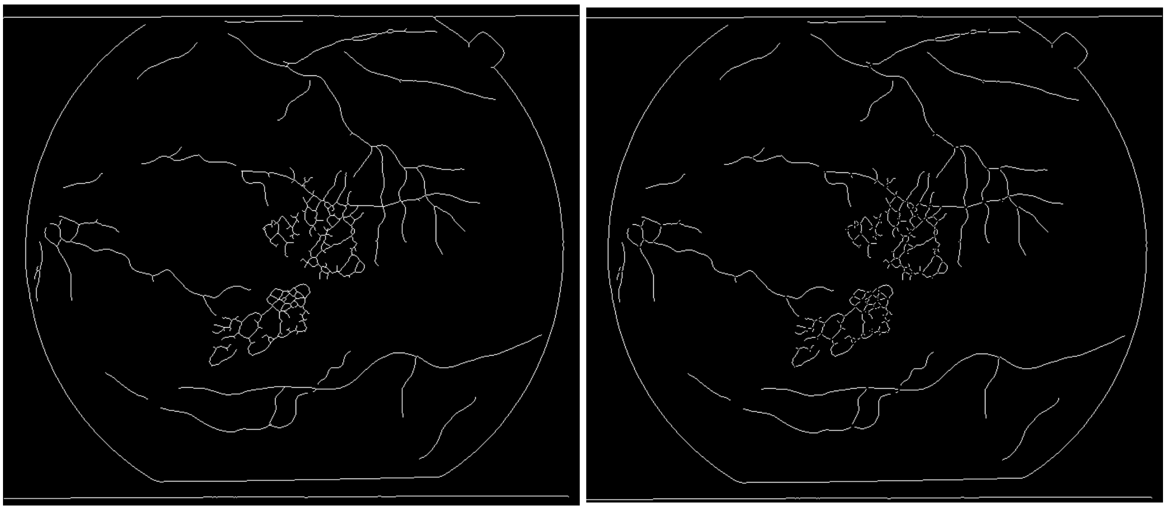


Figure 6: Matched filter response of the image (segmentation level 1 complete)



(a) Vessels obtained after segmentation (b) Final segmented image

Figure 7: Segmentation using threshold probing



(a) Thinned (skeleton) image of the vessels (b) Each vessel broken into a separate segment

Figure 8: Intermediate steps for fuzzy convergence

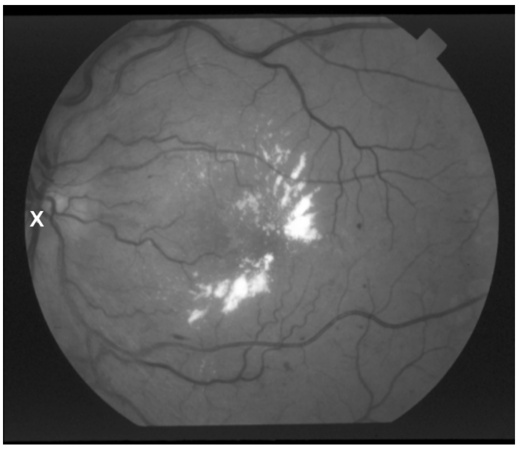
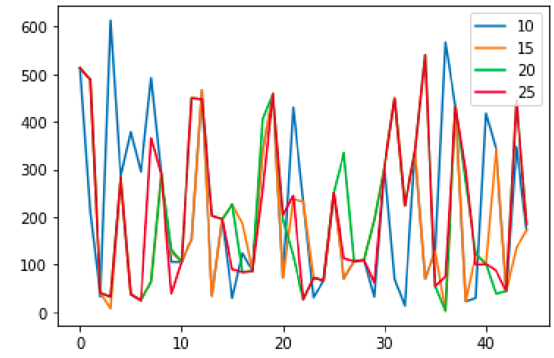


Figure 9: Final image showing predicted location of optic nerve (X)

Experiments

In order to find the hyperparameters which gave the best results, multiple values of t_1, t_2, and R were considered. The results are given in Fig. 10, Fig. 11, and Fig. 12 respectively. The final values selected were $t_1 = 15$, $t_2 = 100$, and $R = 15$.

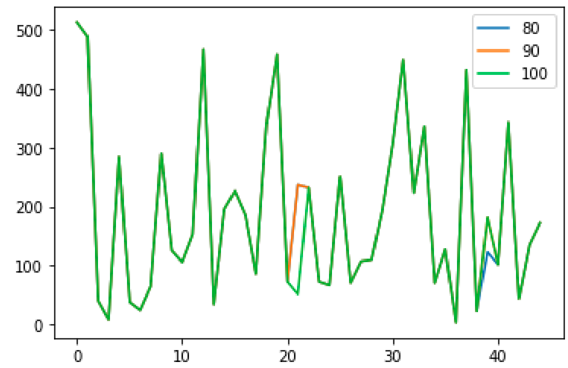


(a) Plot showing the error for each image, for various values of t_1

```
10 : 219.99316359862553
15 : 187.1220984431134
20 : 213.1441243747959
25 : 209.3285913300314
```

(b) The mean error in pixels for various values of t_1

Figure 10: Experiments for various values of t_1

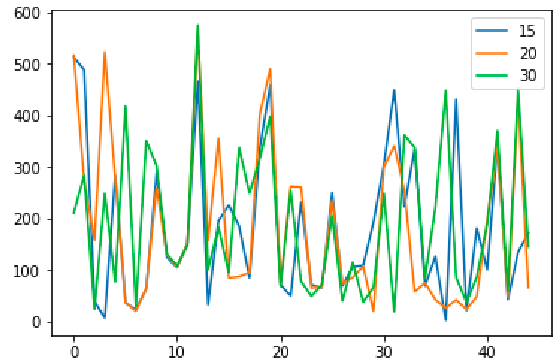


(a) Plot showing the error for each image, for various values of t_2

```
80 : 187.1220984431134
90 : 188.434526618864
100 : 184.31414801126064
```

(b) The mean error in pixels for various values of t_2

Figure 11: Experiments for various values of t_2



(a) Plot showing the error for each image, for various values of R

```
15 : 184.31414801126064
20 : 185.05785215803363
30 : 194.42801490510232
```

(b) The mean error in pixels for various values of R

Figure 12: Experiments for various values of R

Results

For the final performance metric, the optic nerve was considered to be correctly located if the predicted location was within a radius of 100 pixels from the ground truth (since the radius of the optic disc in the given images was of an average size of 100 pixels). The true and predicted locations for each image, mean error, and the number of successful predictions (out of 20) are shown in Fig. 13.

```
1 266 65 (39, 525)
2 262 56 (261, 96)
3 314 455 (342, 172)
4 212 630 (205, 593)
5 271 47 (287, 65)
6 346 595 (469, 405)
7 260 289 (225, 226)
8 248 335 (30, 414)
9 299 366 (366, 339)
10 287 375 (348, 349)
11 307 60 (253, 105)
12 265 323 (172, 381)
13 303 328 (494, 299)
14 294 581 (362, 564)
15 253 454 (454, 72)
16 346 586 (338, 565)
17 292 356 (452, 270)
18 196 35 (142, 121)
19 272 449 (272, 405)
20 315 514 (187, 629)
Mean Error =  148.22467422229812
Number of successful predictions =  10
```

Figure 13: Result of the fuzzy convergence algorithm

Conclusion

The given algorithm has predicted the location of the optic nerve successfully within a mean accuracy of 150 pixels.

The results of segmentation were visualized for each image, and were found to be satisfactory in the sense that most of the major vessels were segmented, while the smaller ones were discarded. The results of the fuzzy convergence algorithm has a success rate of 50%.

Avenues for Further Research

The success rate of 50% can be improved by trying the following modifications to the fuzzy convergence algorithm:

- Increasing the resolution of the fuzzy segment.
- Changing the voting method for convergence. Currently, every fuzzy segment is given a vote of 1, but this could be varied based on the size of the segment.

However, the success rate of 50% for a very simplified fuzzy convergence algorithm shows that modifying the algorithm can lead to better generalization and improvement in performance.

References

[1] S. Chaudhuri, S. Chatterjee, N. Katz, M. Nelson and M. Goldbaum, "*Detection of blood vessels in retinal images using two-dimensional matched filters*," in IEEE Transactions on Medical Imaging, vol. 8, no. 3, pp. 263-269, Sept. 1989, doi: 10.1109/42.34715.

[2] A. Hoover, V. Kouznetsova and M. Goldbaum, "*Locating Blood Vessels in Retinal Images by Piece-wise Threhsold Probing of a Matched Filter Response*", IEEE Transactions on Medical Imaging , vol. 19 no. 3, pp. 203-210, March 2000.

[3] A. Hoover and M. Goldbaum, "*Locating the optic nerve in a retinal image using the fuzzy convergence of the blood vessels*", IEEE Transactions on Medical Imaging , vol. 22 no. 8, pp. 951-958, August 2003.

[4] STARE Project: STructured Analysis of the REtina Project