Development of a New Algorithm for Blood Vessel Segmentation in Retinal Images Using the CVIP Algorithm Test and Analysis Tool

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ABSTRACT

For more than a decade, hundreds of imaging algorithms have been developed and tested for automatically segmenting and identifying the markers of diabetic retinopathy, a major cause of blindness in America. Algorithm development is a time-consuming, labor-intensive process which may involve selecting from and testing a large number of possible combinations of routines, parameters and parameter values. **Purpose:** This paper describes use of the Computer Vision and Image Processing Algorithm Test and Analysis Tool (CVIP-ATAT) which automatically tested thousands of permutations of parameter values in a retinal-image, blood-vessel-segmentation algorithm. **Method:** The effectiveness of the best automatically-developed algorithm was assessed by comparing its segmentations to the segmentations of two manually-developed algorithms using Signal-to-Noise Ratio (SNR), Root Mean Square (RMS) error and Pratt's Figure of Merit (PFM). **Results:** The automatically-developed algorithm was better than manually-developed Algorithms 1 & 2, in terms of SNR by 14.95% and 31.63%, in terms of RMS error by 17.90% and 18.91%, and in terms of PFM by 65.92% and 49.33%, respectively. **Conclusion:** CVIP-ATAT's algorithm worked significantly better than the two manually-developed algorithms. The CVIP-ATAT is an effective tool for automatically developing blood-vessel segmentation algorithms. Consequently, the prospect of using it to develop computer vision and image processing algorithms for other applications is highly-encouraging.

Keywords: Image-Processing Program Synthesis, Automatic Algorithm Test and Analysis, Diabetic Retinopathy, Blood Vessel Segmentation.

1. INTRODUCTION

About 4.1 million Americans suffer from diabetic retinopathy (DR). DR is one of the major causes of blindness in Americans and responsible for 11% of all cases. Timely treatment will prevent severe vision loss in over 50% of eyes tested for the disease [1, 2]. The present epidemic of diabetes, the consequent rapid rise in the cases of DR with a static graduation rate of ophthalmologists from medical schools threaten to create a great burden on America's health care system [2, 3]. Consequently, much research is being devoted to the development of two types of imaging algorithms: image processing algorithms that will segment retinal blood vessels and other markers of DR in retinal images, as well as computer vision algorithms that will screen for the disease using those segmented images [4-10].

Computer vision and image processing (CVIP) algorithms that identify DR in retinal images could incorporate any of a vast number of imaging techniques that may be implemented by a large variety of possible routines whose parameters and parameter values must be optimized. The development, testing and optimization of those routines, their parameters and parameter values are usually done manually. In order to avoid the time-consuming, labor-intensive task of manually developing, testing and optimizing algorithms, over the years there have been sparse attempts at automating these processes [11-15].

This paper describes the practical application of an automatic software testing tool. The purpose of the study was to use the Computer Vision and Image Processing Algorithm Test and Analysis Tool (CVIP-ATAT) to automatically test thousands of permutations of parameter values in a retinal-image, blood-vessel-segmentation algorithm; and to assess the effectiveness of the best ("optimal") algorithm by comparing its segmentations to the segmentations of two algorithms ("Algorithms 1 & 2") that were manually-developed in a previous study [16, 17].

2. MATERIALS

Image Database: Fifteen color retinal images were collected from the Structured Analysis of the Retina (STARE) image database.

Hand-Drawn Images: Images of 15 ophthalmologists' hand-drawn tracings (ideal segmentations) of the retinal blood vessels in the color retinal images mentioned above, were also downloaded from the STARE database. These ideally-segmented images were used as the "gold standard" of vessel segmentation to compare to the CVIP-ATAT-developed algorithm and the two manually-developed algorithms, to make an assessment of the comparative effectiveness of the three algorithms [16].

Software: The CVIPtools (Computer Vision and Image Processing tools) software libraries were used to perform all image processing operations, as well as to calculate the differences between the ophthalmologists' hand-drawn images and the segmented images generated by the three algorithms [16, 18]. The calculations used as metrics for algorithm effectiveness included Signal-to-Noise Ratio (SNR), Root Mean Square (RMS) error and Pratt's Figure of Merit (PFM). The CVIP-ATAT software was developed using CVIPtools' library functions [18].

3. METHODS

The steps in both Algorithms 1 and 2 were used as functions that were inserted into CVIP-ATAT. These functions were sourced from the CVIPtools libraries [18]. During algorithm development, in order to tweak the functions and employ their best parameter values, the comparison metrics (RMS error, SNR and PFM) for each image were automatically calculated and listed by the software. By observation the software user selected the best metric values which dictated the choice of the best segmentation algorithm.

The following is a listing of the functions or steps finally enlisted by the software (see Figure 1): a histogram stretch, Laplacian edge detection, mean filtering, color-to-gray-scale conversion, a second histogram stretch, a binary threshold, adaptive median filtering, a logical not operation and finally, an edge-linking operation [16, 18]. The output images from the final algorithmic step (edge-linking) contained photographic, image-edge artifacts which were removed by subtracting their corresponding outer-ring masks from them. This postprocessing step helped create a better match with the ophthalmologist-segmented images which had no edge artifacts. The outer-ring masks were thresholded with a threshold value of 128.

After that, the 15 images segmented by the software's algorithm were compared to the 15 images segmented by Algorithms 1 and 2, via the degree of match between those images and the ophthalmologists' ideally-segmented images. The metrics for the degree of match were the average SNR, RMS error and PFM of the 15 images generated by each of the three algorithms [16, 18].

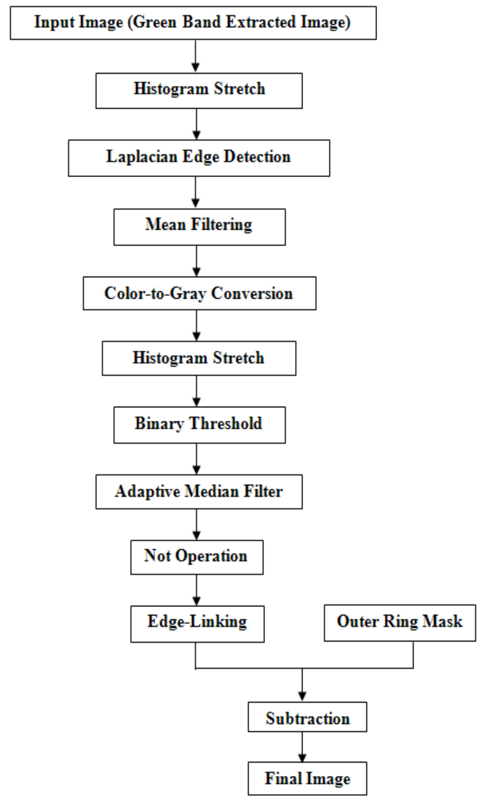

Figure 1. Flow chart of the new algorithm.

4. RESULTS

In terms of SNR, the improvements of the CVIP-ATAT-developed algorithm over manually-developed Algorithms 1 and 2, were 14.95% and 31.63%, respectively. In terms of RMS error, the improvements of the software's algorithm over Algorithms 1 and 2 were 17.90% and 18.91%, respectively. In terms of PFM, the improvements were 65.92% and 49.33%, respectively

The individual SNRs for each image generated by each algorithm are shown in Table 1. The CVIP-ATAT's average *improvements* over Algorithms 1 & 2, in SNR, are shown in Table 2.

Images	SNR for Algorth 1	SNR for Algorth 2	SNR for CVIP-ATAT's Algorth
Image 1	12.140	10.536	13.667
Image 2	11.110	10.136	13.588
Image 3	11.669	10.859	12.523
Image 4	10.774	9.859	13.627
Image 5	12.952	9.055	13.310
Image 6	11.915	9.749	12.890
Image 7	12.296	10.419	13.038
Image 8	11.961	9.981	12.436
Image 9	10.595	9.736	13.019
Image 10	10.948	9.950	13.495
Image 11	10.166	9.016	12.779
Image 12	10.698	9.744	12.712
Image 13	11.747	10.124	12.960
Image 14	11.300	10.873	13.490
Image 15	10.794	9.356	12.197
AVG	**11.404**	**9.959**	**13.109**

Table 1. Individual SNRs for each image output by each algorithm, as well as their average SNRs.

SNR Percent Increase for CVIP-ATAT vs. Alg. 1	SNR Percent Increase for CVIP-ATAT vs. Alg. 2
14.95%	**31.63%**

Table 2. The CVIP-ATAT's average improvements over Algorithms 1 & 2, in SNR.

The individual RMS errors for each image generated by each algorithm are shown in Table 3. The CVIP-ATAT's average *improvements* over Algorithms 1 & 2, in RMS error, are shown in Table 4.

Images	RMS Err for Algorth 1	RMS Err for Algorth 2	RMS for CVIP-ATAT's Algorth
Image 1	63.027	65.810	52.866
Image 2	70.967	69.389	53.354
Image 3	66.545	63.044	60.310
Image 4	73.760	71.773	53.109
Image 5	57.407	70.435	55.084
Image 6	64.684	73.000	57.812
Image 7	61.910	66.837	56.838
Image 8	64.339	70.814	60.919
Image 9	75.295	73.122	56.962
Image 10	72.303	71.105	53.495
Image 11	79.108	80.307	58.556
Image 12	79.730	73.048	59.010
Image 13	65.994	69.492	57.350
Image 14	69.429	62.924	53.958
Image 15	73.595	69.823	62.615
AVG	**69.206**	**70.061**	**56.816**

Table 3. Individual RMS error for each image output by each algorithm, as well as their average RMS errors.

RMS Percent Decrease for CVIP-ATAT vs. Alg. 1	RMS Percent Decrease for CVIP-ATAT vs. Alg. 1
-17.90%	**-18.91%**

Table 4. The CVIP-ATAT'S average improvements over Algorithms 1 & 2, in RMS.

The individual PFMs for each image generated by each algorithm are shown in Table 5. The CVIP-ATAT's average *improvements* over Algorithms 1 & 2, in PFM, are shown in Table 6.

Images	PFM for Algorth 1	PFM for Algorth 2	PFM for CVIP-ATAT's Algorithm
Image 1	0.651	0.669	0.911
Image 2	0.536	0.558	0.730
Image 3	0.642	0.582	0.881
Image 4	0.488	0.516	0.727
Image 5	0.597	0.543	0.721
Image 6	0.620	0.573	0.800
Image 7	0.500	0.580	0.763
Image 8	0.510	0.561	0.865
Image 9	0.382	0.445	0.832
Image 10	0.342	0.451	0.875
Image 11	0.489	0.496	0.810
Image 12	0.441	0.516	0.857
Image 13	0.359	0.525	0.706
Image 14	0.350	0.593	0.914
Image 15	0.421	0.533	0.763
AVG	**0.488**	**0.543**	**0.810**

Table 5. Individual PFMs for each image output by each algorithm, as well as their average PFMs.

PFM Percent Increase CVIP-ATAT vs. Alg. 1	PFM Percent Increase CVIP-ATAT vs. Alg. 2
65.92%	**49.33%**

Table 6. The CVIP-ATAT's average improvements over Algorithms 1 & 2, in PFM.

The visual results of the CVIP-ATAT-developed algorithm are shown in Figure 2.

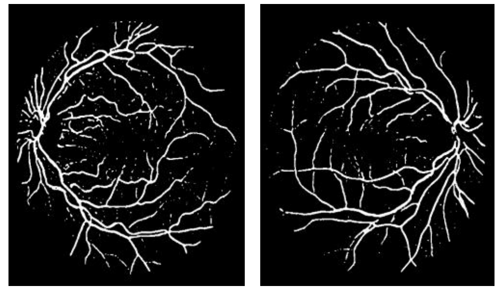

Figure 2. Examples of visual results in the output images of the CVIP-ATAT-developed algorithm.

5. DISCUSSION

Subsequent to this study, further developments of the tool have been made. The ATAT has been developed so that for every algorithm tested, average SNR, RMS error and PFM can now be automatically calculated, sorted and listed in descending order. This allows the user to directly select which algorithm gives better results, without having to review those metrics for every image.

The design framework of the CVIP-ATAT is general enough to allow algorithm development and image analysis for a wide variety of applications. Presently, preparation is being made for the development of automatic dermascopic image analysis and segmentation algorithms. Computer vision applications are possible and planned for the not too distant future.

6. SUMMARY & CONCLUSION

The CVIP-ATAT-developed algorithm proved to be significantly better than the two manually-developed algorithms. CVIP-ATAT algorithm-development software is an effective tool for automatically developing retinal blood-vessel segmentation algorithms. This makes the prospect of using the software to develop computer vision and image processing algorithms for other applications highly-encouraging. This prospect is *especially* encouraging, regarding the race toward the automatic detection of DR for its timely treatment and the prevention of blindness.

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