Robust PCA Unrolling Network for Super-Resolution Vessel Extraction in X-Ray Coronary Angiography

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***Abstract*—Although robust PCA has been increasingly adopted to extract vessels from X-ray coronary angiography (XCA) images, challenging problems such as inefficient vessel-sparsity modelling, noisy and dynamic background artefacts, and high computational cost still remain unsolved. Therefore, we propose a novel robust PCA unrolling network with sparse feature selection for super-resolution XCA vessel imaging. Being embedded within a patch-wise spatiotemporal super-resolution framework that is built upon a pooling layer and a convolutional long short-term memory network, the proposed network can not only gradually prune complex vessel-like artefacts and noisy backgrounds in XCA during network training but also iteratively learn and select the high-level spatiotemporal semantic information of moving contrast agents flowing in the XCA-imaged vessels. The experimental results show that the proposed method significantly outperforms state-of-the-art methods, especially in the imaging of the vessel network and its distal vessels, by restoring the intensity and geometry profiles of heterogeneous vessels against complex and dynamic backgrounds. The source code is available at https://github.com/Binjie-Qin/RPCA-UNet**

***Index Terms*—Algorithm unrolling, RPCA unrolling network, X-ray coronary angiography, vessel extraction, sparse feature selection, super-resolution.**

Manuscript received 14 March 2022; revised 9 May 2022; accepted 21 May 2022. Date of publication 23 May 2022; date of current version 27 October 2022. This work was supported in part by the Science and Technology Commission of Shanghai Municipality under Grant 19dz1200500 and Grant 19411951507; in part by the National Natural Science Foundation of China under Grant 61271320 and Grant 82070477; in part by the Shanghai Shenkang Hospital Development Center under Grant SHDC12019 12; and in part by the Interdisciplinary Program of Shanghai Jiao Tong University under Grant ZH2018ZDA19, Grant YG2021QN122, and Grant YG2021QN99. *(Corresponding author: Binjie Qin.)*

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Digital Object Identifier 10.1109/TMI.2022.3177626

I. Introduction

C[illegible]

, w -w n ( ) n CA . n n n CA n -w n n n- n - k w nn 17 . D n n - nn - n n w k 18 n n- n w- n n n nn /n n- n- CA n n n w k, CA- , n -w w n n n n n (C) n w k 19 . CA- n n n -w n n n n n n CA n n n w . n n n n w n n C n w k. B n n n n CA n , C n w k n n n n . n n n CA . n n n w k

1) A n CA n n (n CA) n w k w -w CA w n n n . n n n w k n n/ n n n -w n n n C n w k. CA- nn n nn - nn n n- n n n n n k n . kn w , CA n n n w k w n CA . E n w n n - - - - n n n n n.

2) W C n w k n n n n CA n n - n n n n n w CA n . C n w k n -w n w k n n n n n n n n - n n n CA n .

3) CA- n w k nn - n n

n , BC (n k- n n) 9 , n nn n n n n CA - n n . w k n n n n n n n n n - n n n nn - n n n n n w k.

II. Related Works

A. XCA Vessel Extraction

C w n w n n 4 , 5 , 20 , n n nn n n n- w n n CA n n . CA n - 21 n n w n n CA n n n : n n n , k n , n n nn n n n 22 25 n /n n- n n n - k n n n w n n n k n . n- n n- 26 n n 27 n n n n n n w n n n n w n 24 , n n 25 , n 23 n n n n k n w n- - n n n n n n n n n n- n n n n. n n n, n - w 22 n w n n 28 CA n n, n n n w n nn n n - k . n n n ,w n n n n n n n n n , - n n n n - n n - n - 29 , 30 - n - k 2D/3D 29 , 31 , n n n n n n n - k k- n n CA .

An n n n , w n n . n 32 n - n n, n n n n w - n n n, n CA w . n n , n n n n w n w k 33 , 34 , w n n - n n n . C n , n n n

B. Unrolling Neural Network

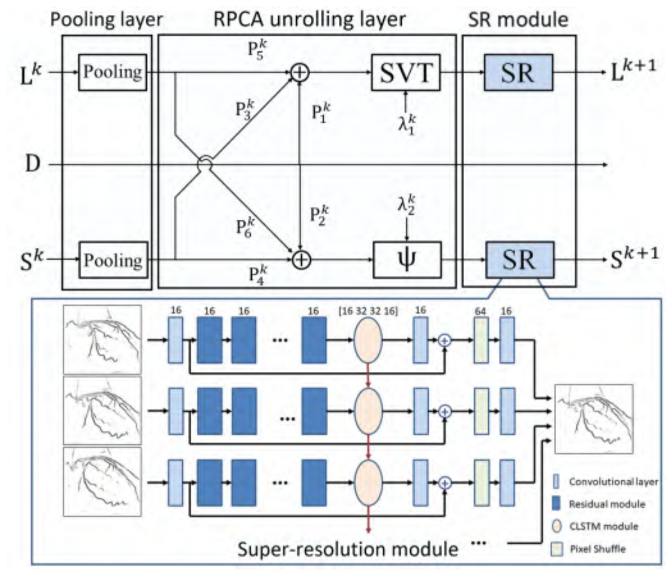

Fig. 1. The architecture of a single iteration/layer of RPCA-UNet for decomposing XCA data *D* into vessel (*S*) and background (*L*) components, which consists of a pooling layer, an RPCA unrolling layer, and an SR module. The SR module is mainly built upon the convolutional layer, residual module and CLSTM network.

III. METHOD

A. RPCA Modelling

(1)

(2)

[illegible] CA [illegible] H_1 [illegible] H_2 [illegible] CA [illegible]

$$\frac{1}{2} \ldots H_1 \ldots H_2 \ldots{}_F^2 \ \lambda_1 \ldots \lambda_2 \ldots{}_{1,2} \quad (3)$$

[illegible] $_{1,2}$ [illegible] $_{1,2}$-n [illegible] λ_1 [illegible] λ_2 [illegible]

$$\ldots \begin{bmatrix} I \\ 0 \end{bmatrix}, \ldots \begin{bmatrix} 0 \\ I \end{bmatrix}, A \ldots \begin{bmatrix} H_1 \\ H_2 \end{bmatrix} \quad (4)$$

[illegible] (3) [illegible]

$$\ldots \frac{1}{2} \ldots D \ldots A \ldots{}_F^2 \ldots (\ ) \quad (5)$$

[illegible] (5) [illegible] 14 [illegible]

$$\ldots \lambda_1 \ldots (I \ldots \frac{1}{\ldots} H_1^H H_1) \ldots H_1^H H_2 \ldots H_1^H D \quad (6)$$

$$\ldots \psi_{\lambda_2} \ldots (I \ldots \frac{1}{\ldots} H_2^H H_2) \ldots H_2^H H_1 \ldots H_2^H D \quad (7)$$

[illegible] λ_1 [illegible] ψ_{λ_2} [illegible]

B. RPCA Unrolling Network

[illegible] 15 [illegible] H_1 [illegible] H_2 [illegible] (6) [illegible] (7) [illegible] H_1 [illegible] H_2 [illegible]

$$\ldots \lambda_1 \ldots D \quad (8)$$

$$\ldots \psi_{\lambda_2} \ldots D \quad (9)$$

[illegible] 1 [illegible] λ_1 [illegible] λ_2 [illegible]

C. Patch-Wise Super-Resolution Module

[illegible] CA [illegible] CA [illegible] λ_1 [illegible] λ_2 [illegible] CA [illegible]

[illegible] 67 [illegible] CA [illegible]

$$\sigma(\ldots) \quad (10)$$

D. Automatic Vessel Labelling

CA- ... CA ... CA- ... CA- ... BC ... 9 ... BC ... CA- ... CA ...

IV. Experimental Results

A. Experimental Materials

... 43 ... CA ... 30 ... 140 ... CA ... 512 × 512 ... 8 ... 800 ...

B. Experiment Settings and RPCA-UNet Training

CA- ... 4 ... 5 ... 1, ... 2 ... 3 ... 1, ... 1 ... ADA ... 0.0001. ... 2 ... 2 ... 2.

CA- ... BC ... 9 ... 64 × 64 × 20 ... (50% ...). ... 15 ... 900 ... 20000. ... 0.6:0.2:0.2, ...

C. Comparison Methods

... BC ... 9 ... CA- ... CA 68 ... CA 69 ... C ... CA 6 ... C ... A 14 ... C 70 ... 27 ... 48 ... C ... 71 ...

D. Visual Evaluation on Experimental Results

... 2, ... CA- ... 2( )-( ) ... C ... A ... 2( )), ...

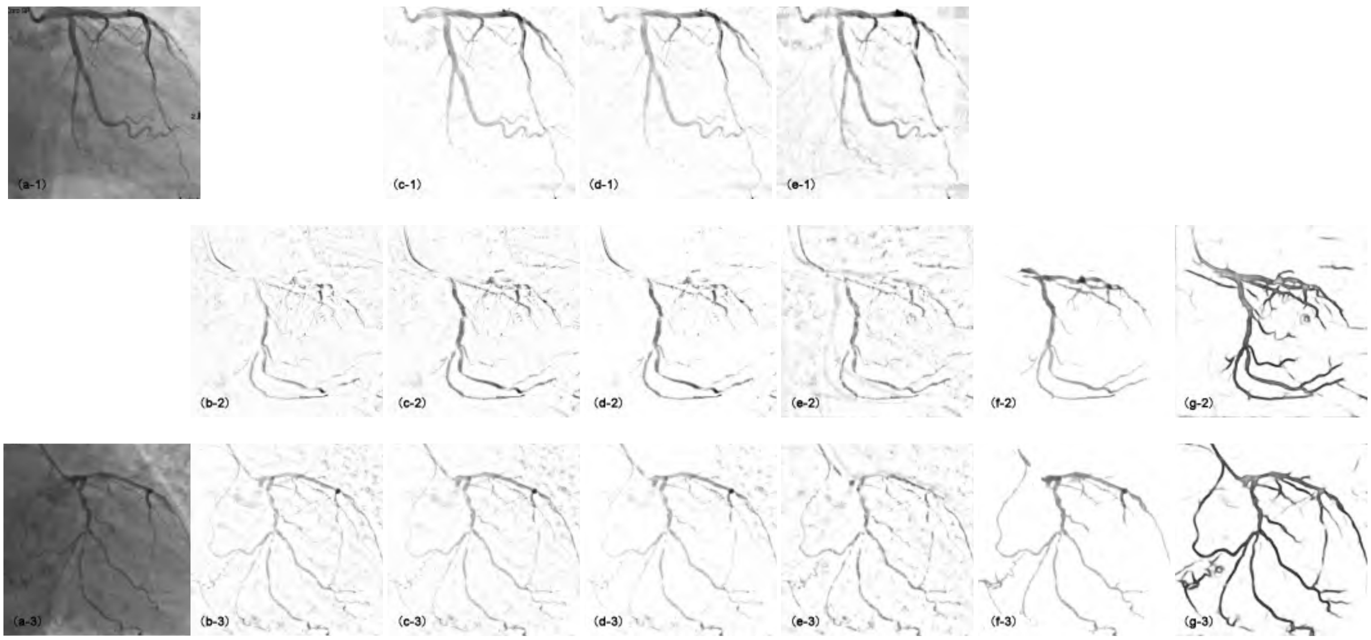

Fig. 2. XCA vessel extraction results. (a) Original XCA image; (b) ALF-RPCA; (c) MoG-RPCA; (d) MCR-RPCA [6]; (e) CORONA [14]; (f) VRBC [9]; (g) RPCA-UNet.

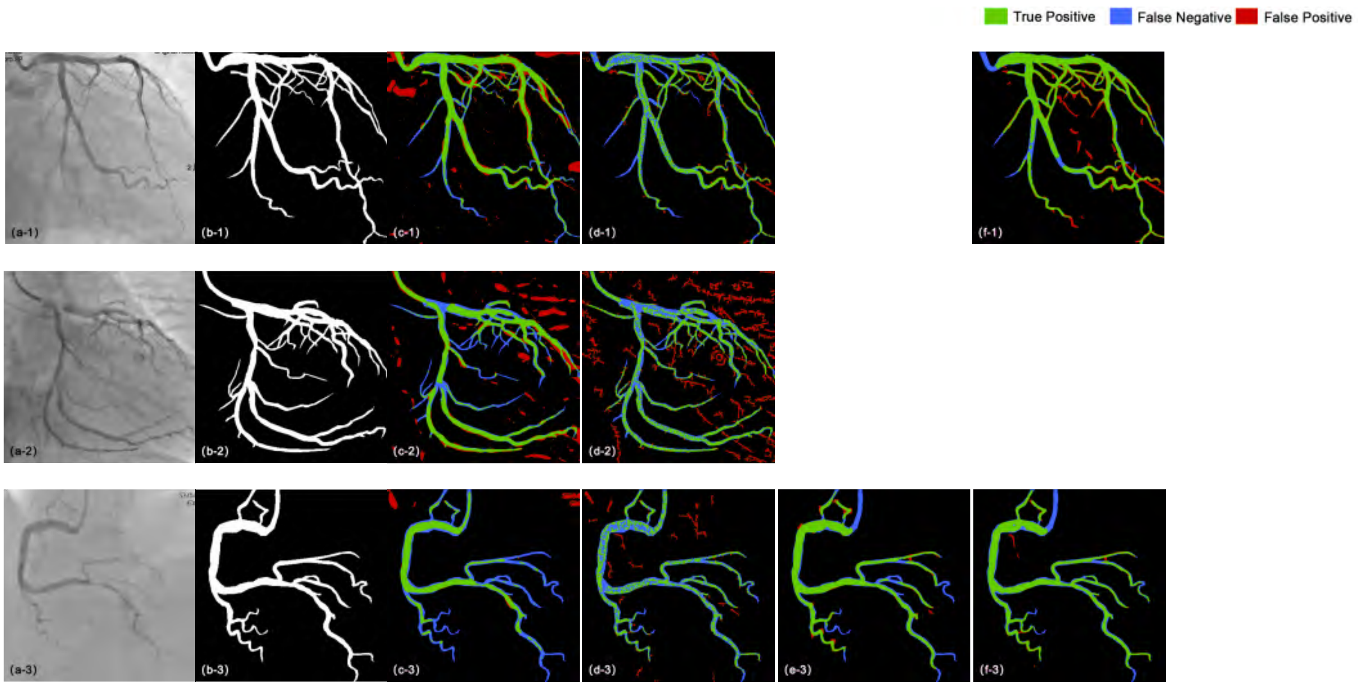

Fig. 3. XCA vessel segmentation results. Pixels labelled with green, blue, and red colours represent true positive pixels, false negative pixels, and false positive pixels, respectively. (a) Original XCA image; (b) Ground-truth vessel mask; (c) Frangi's; (d) Coye's; (e) SVS-net; (f) CS^2-Net; (g) RPCA-UNet.

TABLE I

PERFORMANCE OF DIFFERENT VESSEL EXTRACTION METHODS IN TERMS OF CNR VALUES (MEAN STANDARD DEVIATION)

Fig. 6. The effect of coarse versus fine vessel label on the result of weakly supervised learning. The first row are the coarse and fine grey value labels automatically generated by the VRBC combined with different binary vessel mask segmentations, i.e. from left to right being original segmentation method in the VRBC, SVS-net with training data generated by the original segmentation method, SVS-net with training data by manual annotation; the second row of results are test cases of the corresponding networks trained with different grey value labels.

V. Conclusion and Discussion

Acknowledgment

REFERENCES

1 . , D. B wn, , A. n , . k w , n . k, C n n n n (n n- n n - n), C . ., . 116, n . 4, . 771 786, . 2020.

2 . , . B , n . D n , A n n n n n n - , . A ., . 28, . 33 45, . 2016.

3 . , , , n B. n, n n n w n n CA, *IEEE* . ., . 28, n . 11, . 5537 5551, . 2019.

4 . , E. D , . E. , n . . , B n n w , n , C . . B ., . 158, . 71 91, 2018.

5 D. n . n , n n - k n : A w, C . . . G ., . 89, A . 2021, A . n . 101840.

6 . n, . , . n , n B. n, E n n - n - n CA w n n n n, tt ., . 63, . 653 666, . 2017.

7 . , A. n n, E. , . n, n . , A n n n n n n - n n n n n, . A ., . 39, . 145 161, . 2017.

8 . n, D. , . D n , n B. n, w- nk n - n w n n 2D . B ., . 63, n . 17, 2018, A . n . 17 01.

9 B. n *et al.*, A n n n k n n - n n , tt ., . 87, . 38 54, . 2019.

10 . n *et al.*, n n n , *IEEE* . C ., . 30, n . 2, . 442 456, . 2020.

11 . n *et al.*, - n n n n n n n - n n , *IEEE* . C ., . 30, n . 10, . 3558 3570, . 2020.

12 . *et al.*, n n - n n - n , *IEEE* . B . E ., . 67, n . 5, . 1338 1348, 2020.

13 . B w n, . , . n , . n, n . , n n CA n n n , . *IEEE*, . 106, n . 8, . 1427 1457, A . 2018.

14 . n *et al.*, D n CA w n n n n , *IEEE* . ., . 39, n . 4, . 1051 1063, A . 2020.

15 . n , . , n . C. E , A n n : n , n n n n n n , *IEEE* ., . 38, n . 2, . 18 44, . 2021.

16 . n . C n, n n -561.1(71)-434n98( )23 -1 71 .3( )-62 1 5

47 [illegible] *IEEE A*[illegible] 6, [illegible] 44635 44643, 2018.

48 D.[illegible] 128, [illegible] 172 187, A[illegible] 2020.

49 [illegible] *B*[illegible] *C*[illegible] 68, [illegible] 2021, A[illegible] n. 102646.

50 [illegible] *C*[illegible] *B*[illegible] 198, [illegible]n. 2021, A[illegible] n. 105769.

51 [illegible] *IEEE* [illegible] 40, n. 5, [illegible] 1329 1339, [illegible] 2021.

52 [illegible] C. E[illegible] *IEEE* [illegible] 69, [illegible] 3699 3713, 2021.

53 [illegible] A n w[illegible] 300, [illegible] 70 79, [illegible] 2018.

54 [illegible] B[illegible] *IEEE* [illegible] 5, n. 4, [illegible] 537 550, [illegible] 1994.

55 [illegible] C. [illegible] α-[illegible] *IEEE* [illegible] 42, n. 11, [illegible] 2960 2966, [illegible] 2020.

56 [illegible] A[illegible] *F*[illegible] 50, [illegible] 158 167, [illegible] 2019.

57 [illegible] A n[illegible] 565, [illegible] 278 305, [illegible] 2021.

58 [illegible] C.[illegible] *IEEE* [illegible] *C*[illegible] 51, n. 3, [illegible] 1747 1756, [illegible] 2021.

59 A.[illegible] A.[illegible] D.[illegible] A[illegible] *E*[illegible] *A*[illegible] 183, [illegible] 2021, A[illegible] n. 115312.

60 [illegible] D.[illegible] A[illegible] *IEEE* [illegible]