Edge-guided Localized Phase Unwrapping: Application to SWI

H. Thayyullathil[1], L. Stables[1], M. W. Weiner[1], N. Schuff[1]

[1]Magnetic Resonance Unit, DVA Medical Center and University of California San Francisco, San Francisco, California, United States

INTRODUCTION

Accurate measurement of phase is essential in many contexts in MRI, such as in susceptibility-weighted imaging (SWI), flow imaging, and Bo field-maps. In such situations, artificial discontinuities in phase images called 'phase wraps' are not desirable. Many algorithms have been proposed in the past for phase unwrapping. They can be broadly classified into path-following methods [1][2] (which perform phase correction guided by branch cuts, quality maps etc.) and minimum-norm methods [3][4] (which unwrap phase by minimizing the norm of difference between the gradients of wrapped and unwrapped phase along orthogonal directions). The path-following methods are computationally very intensive and the minimum-norm methods smoothen out subtle features in phase images. In an attempt to formulate an efficient algorithm that addresses both these problems, we have designed and implemented a new method that alters the phase values only at regions of wraps, which are automatically identified by linked edges present in the wrapped phase image.

THEORY

The inspiration for this new phase unwrapping procedure is the physical analogy of finding folds on a sheet and unfolding them one by one. The 'folds' are found out from the edge map of the phase image $\phi(i, j),\ i = 0, 1, \ldots M-1;\ j = 0, 1, \ldots N-1,$ which is obtained as

$$e(i', j') = \begin{cases} 1, & \nabla^2\phi(i, j) \geq T \\ 0, & Otherwise \end{cases} \quad ; i' = 0,1,\ldots M-2;\ j' = 0,1,\ldots N-2,$$

where, '∇^2' is the discrete Laplacian operator and 'T' is a threshold. The resulting edge map is subjected to edge-linking and all linked edges (fringe-lines) are retained for further procedures. Phase values are corrected across the fringe-lines by adding 2π to them, while scanning through the phase image in the direction perpendicular to the fringe-lines. The scanning direction is calculated as $\pi/2 + tan^{-1}(\nabla_y\phi/\nabla_x\phi)$, where ∇_y and ∇_x are the gradient operators along x and y directions.

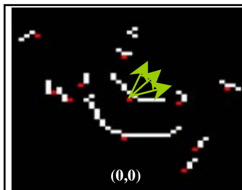

Fig. 1: The unwrapping is per-formed perpendicular to the edge points

METHODS

We have tested the algorithm on both simulated and experimental data. A two dimensional Gaussian function was used as a synthetic object. By appropriately choosing the steepness of the Gaussian function, we obtained phase wraps of desired separation, as depicted in Fig. 2b. We applied the algorithm to experimental SWI data, which involves the standard high-pass phase filtering procedure as explained in [5]. A representative example of SWI phase image is shown in Fig. 3b. While there are subtle features near the centre of the SWI phase map that are important to be retained, severe phase wraps are seen in anterior regions close to the frontal and nasal sinus cavities. Minimum-norm based methods can unwrap these severe phase wraps but subtle phase features are smeared out after unwrapping. The procedures of the new phase unwrapping algorithm, formulated to perform unwrapping while retaining the subtle features in the phase image, can be summarized as follows:

1. Detect and link edges in the phase image.
2. Form sets of coordinates of the points in each fringe-line. For each fringe-line, find a seed point right behind it and assign a scanning direction. Fig. 1 schematically shows the seed points (red dots) and possible scanning directions for a fringe-line.
3. Enlist and sort the seed points in the increasing order of proximity from the centre of the image. (This step is based on the assumption that the phase in the centre of the SWI phase map is least wrapped).
4. Scan along the respective scanning directions through the image; starting from the first seed in the seed list, adding 2π to the phase values as the discontinuities are encountered. Continue the scan until it hits another edge point or exits the object.

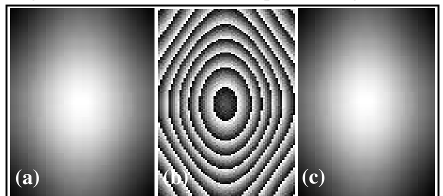

Fig. 2: **(a)** 2D Gaussian function. **(b)** Wrapped version of (a). **(c)** The result of unwrapping using the new algorithm

RESULTS

Synthetic data without and with phase wrapping are shown in Fig.2(a) and Fig. 2(b) respectively. The result of phase unwrapping is shown in Fig. 2(c). Magnitude and phase image of an experimental SWI data set are shown in Fig. 3(a) and Fig. 3(b) respectively. The phase image is multiplied with a brain mask calculated from the magnitude image to avoid unnecessary phase unwrapping in regions outside the brain. The unwrapped SWI phase map is shown in Fig. 3(c). Clearly, the algorithm has unwrapped the phase, while retaining the subtle features (as in Fig. 3(d)) throughout the SWI phase map. The algorithm was coded in MATLAB and required about 20 seconds for unwrapping a 448 x 352 SWI phase image.

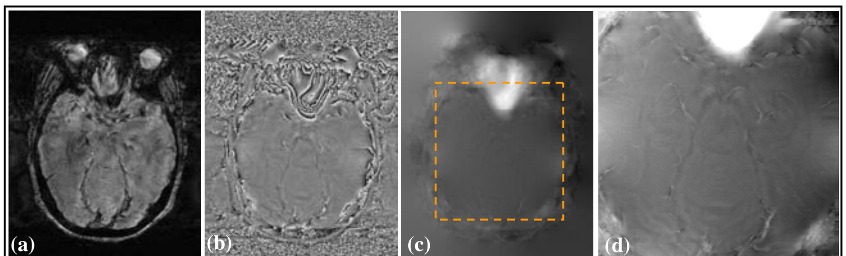

Fig. 3: **(a)** The SWI magnitude image. **(b)** The SWI phase image with phase wraps **(c)** The result of unwrapping using the new algorithm **(d)** Blow-up of a region in the unwrapped phase map to show that the subtle features are preserved.

DISCUSSION

We have designed and implemented a new and straightforward phase unwrapping procedure, which performs phase unwrapping only at locations of phase wraps, guided by linked edges in the wrapped phase data. Implementation of the method for 3D volumes involves area segments instead of linked edges, which is a work in progress. Unlike the standard region growing methods, closed regions are not necessary, which reduces the computational complexity of the method. The primary limitation is the signal to noise ratio (SNR) of the complex data. At poor SNR, linking edges accurately is challenging, which asks for very robust edge-linking techniques.

REFERENCES

[1] R. M. Goldstein, H. A. Zebker and C. L. Werner, *Radio Science*, **23 (4)**, pp. 713-720, 1988.
[2] T. J. Flynn, *Journal of Optical Society of America A*, **14 (10)**, pp. 2692-2701, 1997.
[3] D. C. Ghiglia and L. A. Romero, *Journal of Optical Society of America A,* **11 (1)**, pp. 107-117, 1994.
[4] S. M. Song, S. Napel, N. J. Pelc and G. H. Glover, IEEE Trans. Image Processing, **4 (5)**, pp. 667-676, 1995.
[5] E. M. Haacke,Y. Xu, Yu-C. N. Cheng, and J. R. Reichenbach, *Magnetic Resonance in Medicine,* **52 (3)**, pp. 612-618, 2004.

ACKNOWLEDGEMENTS

We thank E. Mark Haacke, Bernd Kuehn and Yingbiao Xu for providing us the SWI sequence.