

Robust Phase Unwrapping using a Sorted List, Multi-clustering Algorithm

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Purpose

Many phase processing algorithms, such as referenceless proton resonance frequency (PRF) shift thermometry [1, 2] require unwrapped phase maps. For applications in MRI, methods that minimize global cost functions (PRELUDE, [3]) or unwrap phase by region growing (Φ UN, [4]) have been extensively validated. However, for real-time monitoring of temperature, fast, robust, and fully automated phase unwrapping is prerequisite [5]. In this work, a novel fast, automated phase unwrapping algorithm appropriate for referenceless PRF thermometry is proposed.

Methods

The prototype of this algorithm was implemented with *MathWorks Matlab R2011*. All processing time measurements were performed on a laptop computer (*Dell Latitude E6420, Intel Core i5-2520M, 4 GB RAM*).

Pseudo code formulation of the proposed algorithm is shown in Fig. 1. First, all pixels of the complex MR image are sorted according to their magnitude values in descending order. Then, for each pixel it is checked if there is already corrected neighbors. If the pixel has corrected neighbors, it will be added to the same cluster as its first corrected neighbor. Otherwise, a new cluster for this pixel will be created and the next pixel will be processed. If there is an absolute phase difference of more than π between the pixel and its first corrected neighbor, phase will be corrected by adding multiples of 2π . If more neighbors exist, which are in different clusters, the pixel connects existing clusters of corrected pixels. In this case, there might be also phase offsets between these clusters, which need to be corrected. If the absolute phase difference between the new pixel and the additional clusters is more than π , phase offsets of multiples of 2π will be applied to all pixels of each additional cluster. The algorithm terminates when processing of the full list of pixels is completed. A magnitude threshold can be applied to reduce the computation time by stopping earlier and eliminating processing of low magnitude pixels (e.g. air).

The implementation of the algorithm processes 2D and 3D data. However, the algorithm can easily be extended to process n-dimensional data by modifying the neighborhood definition.

Results

Figure 2 shows a wrapped phase map of a patient's head acquired during a laser-induced interstitial thermal therapy (LITT) at 1.5T. The corresponding unwrapped phase and the estimated temperature map are presented in Fig. 3. Inside the brain, phase was unwrapped without errors. In total, the unwrapping algorithm was successfully applied to 474 images of 4 patients. The processing of the full 256×256 pixel images took 2.1 ± 0.2 s. After applying a magnitude threshold of 5% of the maximum magnitude to exclude air pixels, the total processing time was reduced to 0.30 ± 0.06 s. If the unwrapping is restricted to a common region of interest (ROI, cf. Fig. 2) for thermometry, processing time will be decreased to 34 ± 2 ms.

Discussion

The proposed algorithm has been demonstrated to operate robustly *in vivo*. Because of the order of unwrapping, low magnitude pixels with noisy phase do not contribute to unwrapping artifacts in high magnitude regions. The processing time for common ROIs in referenceless PRF thermometry of less than 40 ms allows for online updates of temperature maps without noticeable delay. The impact of motion on the dynamic stability of the algorithm still requires additional investigation.

Acknowledgements

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References

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INPUT complex MR image data
list := sort all pixels descending by magnitude
FOR each pixel on the list
  IF pixel has already corrected neighbors in image
  THEN
    Add pixel to cluster of first neighbor
    IF phase difference to neighbors in cluster >  $\pi$ 
    THEN
      Correct phase of pixel by multiples of  $2\pi$ 
    END IF
  IF there is more neighbors in different clusters
  THEN
    Merge clusters
    IF phase difference between clusters >  $\pi$ 
    THEN
      Correct phase of clusters by multiples of  $2\pi$ 
    END IF
  END IF
  ELSE
    Add pixel as new single pixel cluster
  END IF
END FOR
```

Fig. 1: Pseudo code of algorithm.

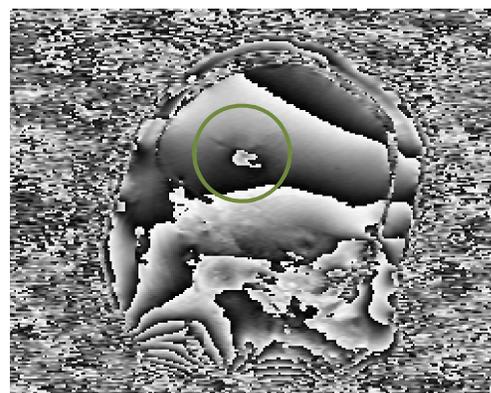


Fig. 2: Measured phase (head of LITT patient) and thermometry ROI (green circle).

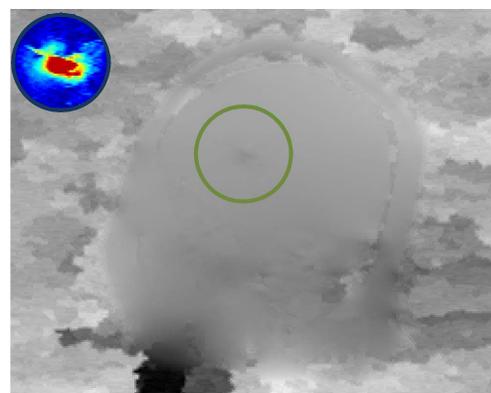


Fig. 3: Unwrapped phase and temperature map (colored, 35 – 65 °C) of thermometry ROI (green).