Limited angle Optical Diffraction Tomography with iterative image-domain masking

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Outline

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2. Proposition: TVIC regularization strategy
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   2. Projection algorithm vs diffraction algorithm (+TVIC)
   3. Importance of amplitude in complex projections?
   4. Optimal number of projections?
4. Experimental verification
Motivation

- 3D analysis of biological microstructures directly on a Petri dish, in real time

http://www.thetimes.co.uk

Motivation

**Problem:** missing cone of projection angles

- Filtered Backpropagation does not apply → iterative solvers
- Non-negativity constraint (NNC) not sufficient for missing data restoration → image artifacts
- Edge-preserving regularization methods (EP, TV) destroy finer structures → limited category of objects
Motivation

Fig. 4. Experimental results of RBC RI tomograms obtained with (a) FT, (b) GP, (c) EP, and (d) TV regularization. The white dotted lines represent the slices of the complementary figures. All scale bars are 3 μm.

Objective:

• To eat a cookie and have a cookie

Retrieve boundaries of non-piecewise-constant objects without blurring the internal structure.
Additionally: minimize distortion of internal structures near the reconstructed boundaries
Proposition: TVIC scheme

**Total Variation Iterative Constraint (TVIC)**

1. TV reconstruction (Chambolle-Pock, ASTRA Toolbox)
2. LAT reconstruction with NNC + 3D mask (binarized and apodized TV image)

Axial image elongation is prevented by the TVIC mask (by confining the reconstruction volume within well detected borders). **However:**

- Is it possible to preserve/enhance internal structures?
- Does the type of the LAT solver matter (projection/diffraction)?
- Are projection amplitudes important (in diffraction case)?
- How many projections are needed?
Synthetic sinogram generation
(complex projections)
Fourier Diffraction Theorem

\[ \hat{O}(K_x, K_y, K_z) = 2ik_z \cdot \hat{U}_R(k_x, k_y; z = 0) \]

\[ O(x, y, z) = k_m^2 \left( 1 - \frac{n^2(x, y, z)}{n_m^2} \right) \]

\[ U_R(x, y) = \ln[U(x, y)] \]

\[ K = k - k_m \]
Synthetic sinogram preparation

object scattering potential → FFT → cubic interpolation → sampling in points lying on Ewald spheres
→ orthogonal projection to (kx,ky) plane → IFFT → Rytov field → complex amplitude of optical field

object padding → upsampling → spectrum → projection: replica overlapping reduced
LAT reconstruction algorithms
Generalized Data Replenishment Algorithm (GDRA)

- ASTRA Toolbox

Non-Negativity Constraint (NNC)

\[ n < n_m \Rightarrow n = n_m \]

+TVIC
(2) Diffraction solver

Iterative Fourier Transform Algorithm (IFTA)

1. Insert projection data
2. Non-Negativity Constraint (NNC)
   \[ n < n_m \Rightarrow n = n_m \]
3. Add TVIC

(FFT-3D)\(^{-1}\)
(iterations)

(FFT-3D)
Numerical reconstructions
(refractive index)
(1) Projection solver

GDRA

GDRA + TVIC

(a)

(b)

(c)

(d)

(e)

(f)
(2) Diffraction solver

FTRA vs. FTRA+TVIC

(a) 3D plot for FTRA

(b) Iteration number vs. Qav(%) for FTRA

(c) RMS vs. phi [deg] for FTRA

(d) 3D plot for FTRA+TVIC

(e) Iteration number vs. Qav(%) for FTRA+TVIC

(f) RMS vs. phi [deg] for FTRA+TVIC

Qav=97.57%

Qav=98.97%
Reconstructions

FTRA 27 iterations

\( \lambda = 0.633 \text{ nm}, \ NA = 1.3, \ \alpha = 45^{\circ} \)
Reconstructions

FTRA+TVIC 5 iterations

$\lambda = 0.633\text{ nm}, NA = 1.3, \alpha = 45^\circ$
Projection amplitudes

GDRA+TVIC

FTRA+TVIC (ph-only)

FTRA+TVIC
Quality of reconstructions by FTRA(+TVIC) solver fed by different projection subsets of the original sinogram (360 views in conical pattern):
(a) one mask for all points, calculated from the full sinogram (idealized case);
(b) one mask per point, calculated from corresponding limited subset of projections (realistic case); the dotted curves correspond to an alternative projection subset chosen from the same full sinogram in a pattern shifted azimuthally by 1 degree.
Experimental verification
IR mask generation

Experimental data

FTRA

Chambolle-Pock (200 iterations)

TVIC mask
C2C12 muscle cell

Experimental data

IFTA
50 iterations

IFTA+TVIC
5 iterations

(a) (c) (e) (g) (i)

(b) (d) (f) (h) (j)

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C2C12 muscle cell

Experimental data

FTRA 50 iterations
**C2C12 muscle cell**

**Experimental data**

**FTRA+TVIC** 5 iterations
Conclusion

- Is it possible to preserve/enhance internal structures?  
  Yes.

- Does the type of the LAT solver matter (projection/diffraction)?  
  Not really.

- Are projection amplitudes important (in diffraction case)?  
  Yes.

- How many projections are needed?  
  ~120

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TODO

- Optimal choice of TVIC mask parameters (threshold + blur)
- Stop condition for the main loop
- Experimental verification with a known object (3D print)
Acknowledgments
TVIC with GDRA (projection solver)

- TVIC with parallel-ray approx. tomographic solver has much faster convergence compared to GDRA approach (9 iterations vs 96 iterations)
- The result is of significantly higher quality with the TVIC approach (average quality index 98.24% vs 96.19%)
- Computing time for TVIC is significantly longer (it takes about 6 mins to calculate the mask)
TVIC with FTRA (diffraction solver)

Addition of TVIC to FTRA provides:
- improvement of image quality in the most distorted regions (+1.4% in averaged QI)
- quick FTRA convergence, but for the price of sharp optimum for number of iterations, not known in general (here 5 or 6 iterations).

- Unlike GDRA, FTRA exhibits tendency to overestimate RI levels in the central horizontal plane $\rightarrow$ optimal number of iterations should not be exceeded
- IFTA+TVIC on CPU is faster than GDRA+TVIC on CUDA $\rightarrow$ 7 minutes instead of 25 minutes for 360 projections
General conclusions

TVIC: Iterative reconstruction with an optimized quasi-binary mask as a spatial constraint limiting the reconstruction volume.

- TVIC sharpens the horizontal boundaries of the object without disturbing the internal structures, provided that the iteration number is kept small.
- Additionally, TVIC can improve reconstruction of structures located in vicinity of the top and bottom borders (normally blurred and dumped due to missing projection angles).
- Compared to GDRA+TVIC, FTRA+TVIC provides more detail with much less computational effort.
- However, the accuracy boost with TVIC is stronger for GDRA.

- In absence of measurement noise, inclusion of amplitude patterns in projection fields has bigger impact on image quality than accounting for scattered field in phase-only projections.