Challenges and progress in physical tomographic reconstruction of light doses for volumetric additive manufacturing

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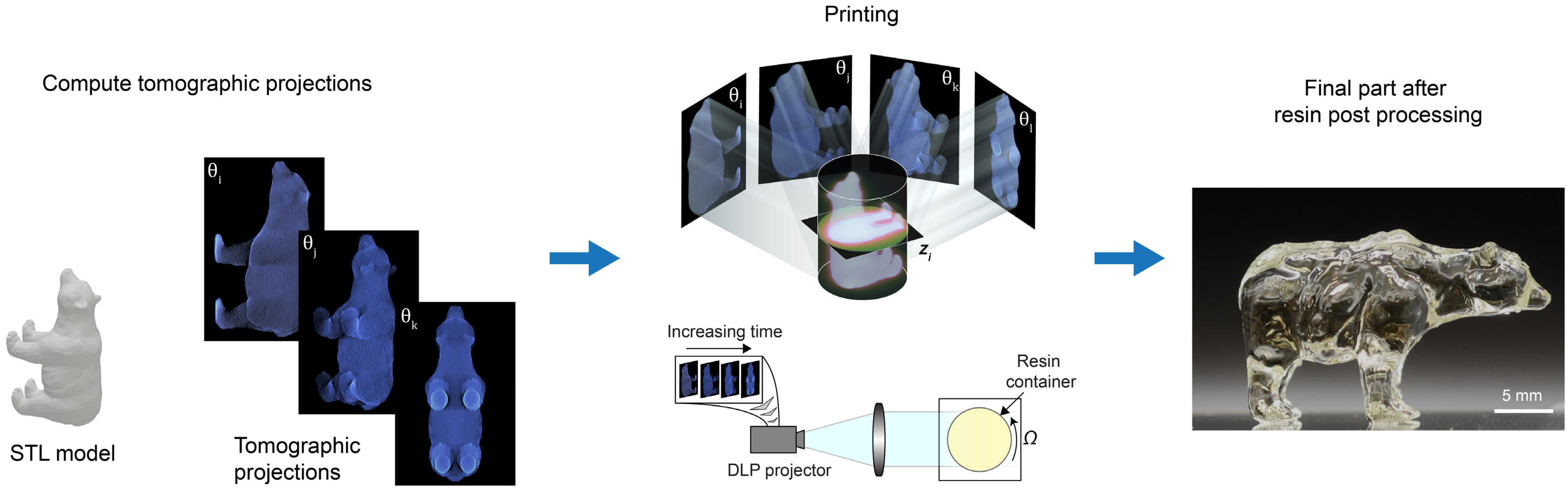
Computed Axial Lithography – a tomographic volumetric additive manufacturing (VAM) technique



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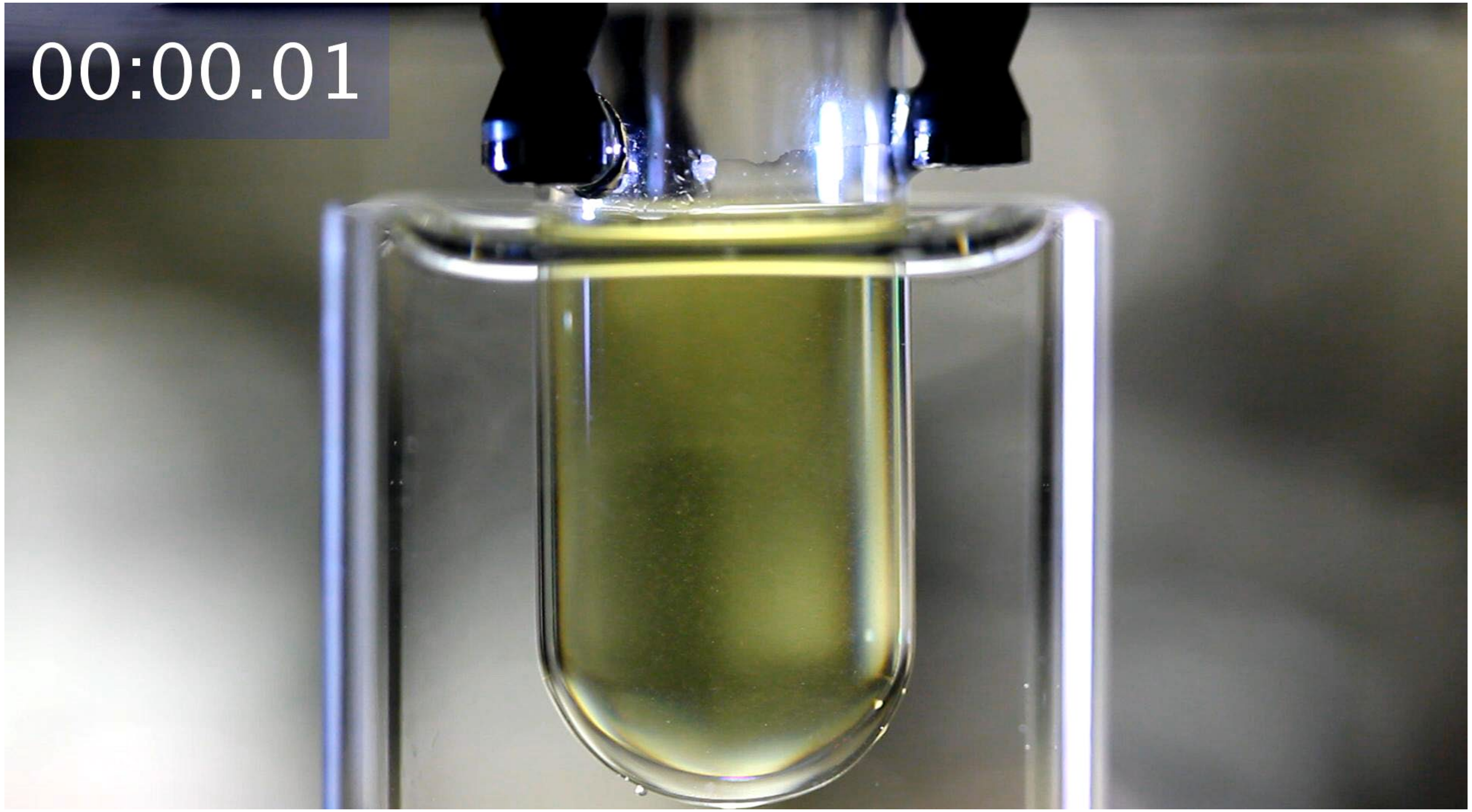
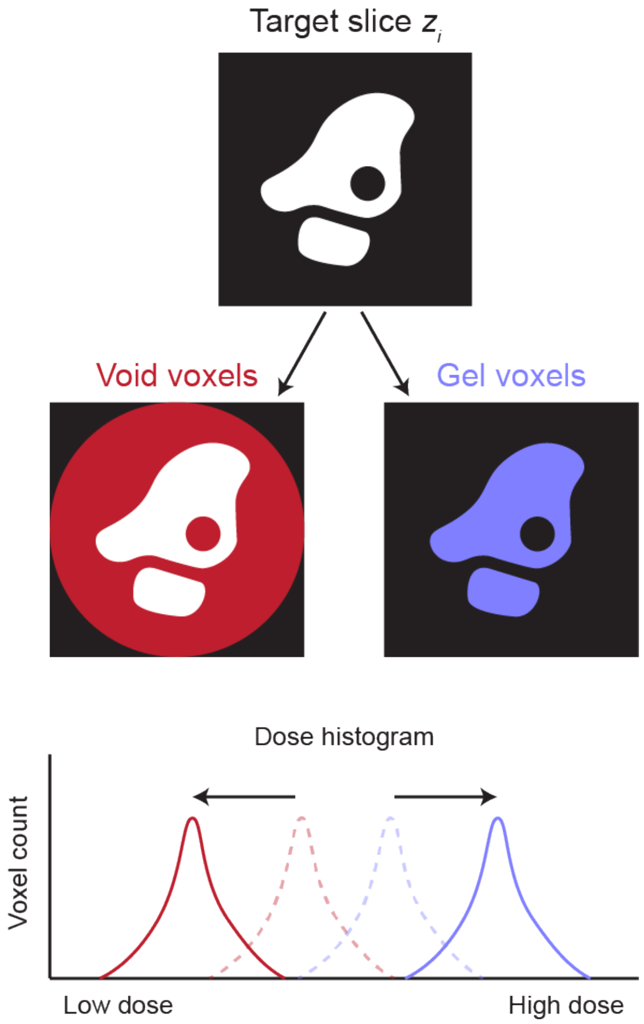
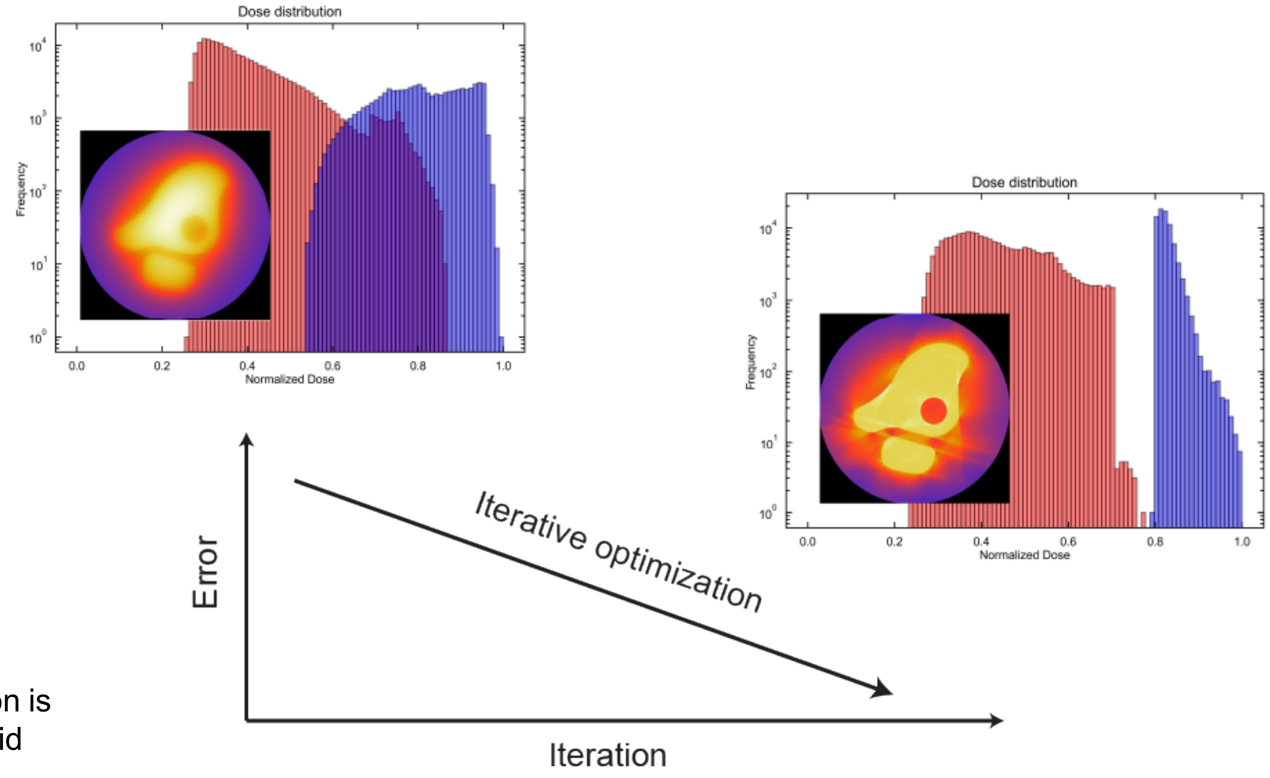


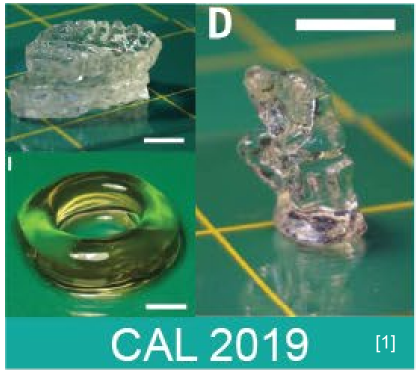
Why do we need to optimize the digital light projections?



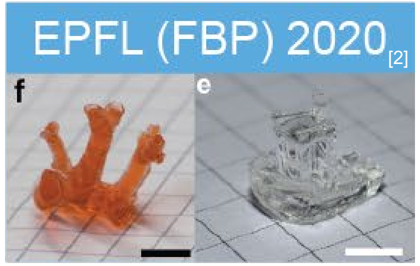
Goal of optimization is to push gel and void dose distributions apart to achieve **high dose contrast**



Various optimization techniques have been developed since the introduction of tomographic VAM



Heuristic penalty (L1) minimization through finite difference approximate gradient descent



Filtered and positivity constrained backprojection, no optimization

Analytic least squares (L2) minimization through conjugate gradient descent

Analytic penalty (L1) minimization (PM) through L-BFGS quasi-Newton algorithm

Robust object-space model optimization (OSMO) through zeroth order method

[1] B. Kelly, I. Bhattacharya, H. Heidari et al. *Science*. **363**. (2019)
[2] D. Loterie, P. Delrot, C. Moser. *Nat. Comms.* **11.** (2020)
[3] C. Cook, E. Fong, J. Schwartz et al. *Adv. Mat.* **32.** (2020)
[4] M. Shusteff, K. Champley, E. Fong et al. US Pat. No. 20220011742
[5] I. Bhattacharya, J. Toombs, H. Taylor. *Additive Manufacturing*. **47**. (2021)
[6] C. Rackson, K. Champley, J. Toombs et al. *Additive Manufacturing.* **48**. (2021)
[7] J. Toombs, M. Luitz, C. Cook et al. arXiv: 2110.01651 (2021)

Tomographic VAM algorithms span 0th to 2nd order methods with varying complexity

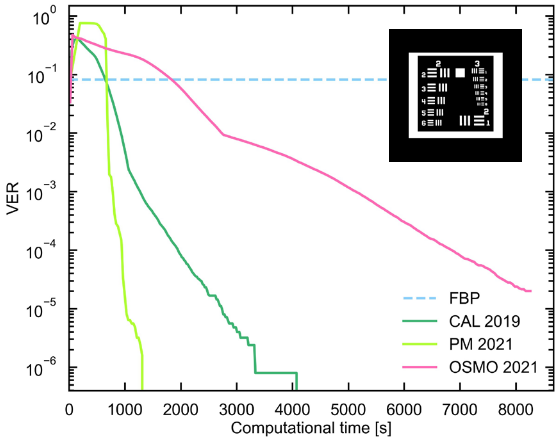
	CAL 2019	EPFL (FBP) 2020	LTT 2020	PM 2021	OSMO 2021
Optimization space	Projection	NA	Projection	Projection	Object
Analytical cost function	No	NA	Yes	Yes	NA
Order	1st	NA	2nd	2nd	0th
p (ℓ_p-norm)	1	NA	2	1	NA
Computational complexity (2D)*	$\mathcal{O}(n^2)$	$\mathcal{O}(n^2 \log n^2)^*$	Unknown	$\mathcal{O}(mn^2)^*$	$\mathcal{O}(n^2)$
Space complexity (2D)*	$\mathcal{O}(n^2)$	$\mathcal{O}(n^2)$	Unknown	$\mathcal{O}(mn^2)^*$	$\mathcal{O}(n^2)$
Open-source	Yes	Yes	No	Yes	Yes

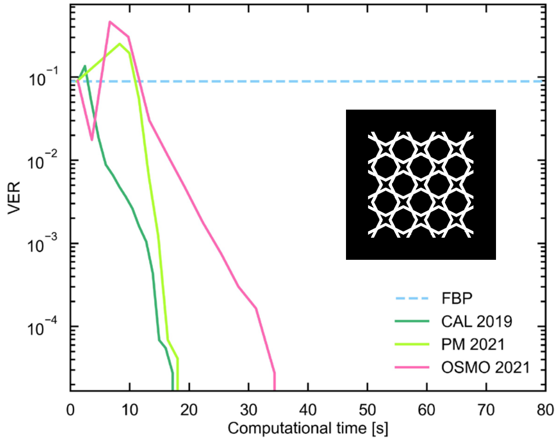
* n is # of pixels/voxels on a side of the target matrix

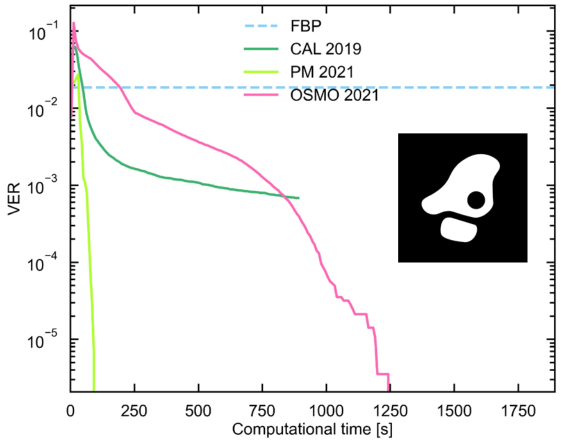
* Not an iterative method, only requires forward and backprojection and 1 FFT and 1 IFFT

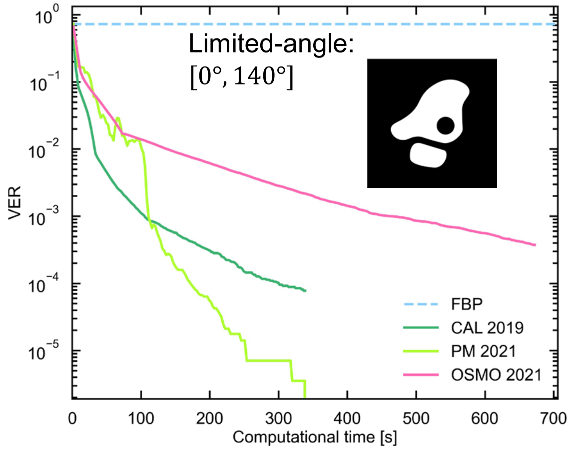
* m is # of historical steps stored to reconstruct approximate inverse Hessian in L-BFGS algorithm

Performance trends







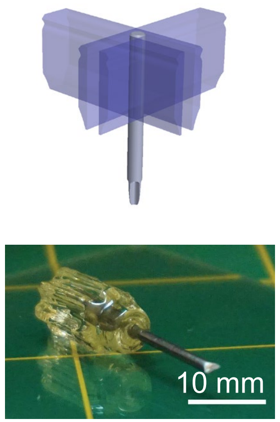


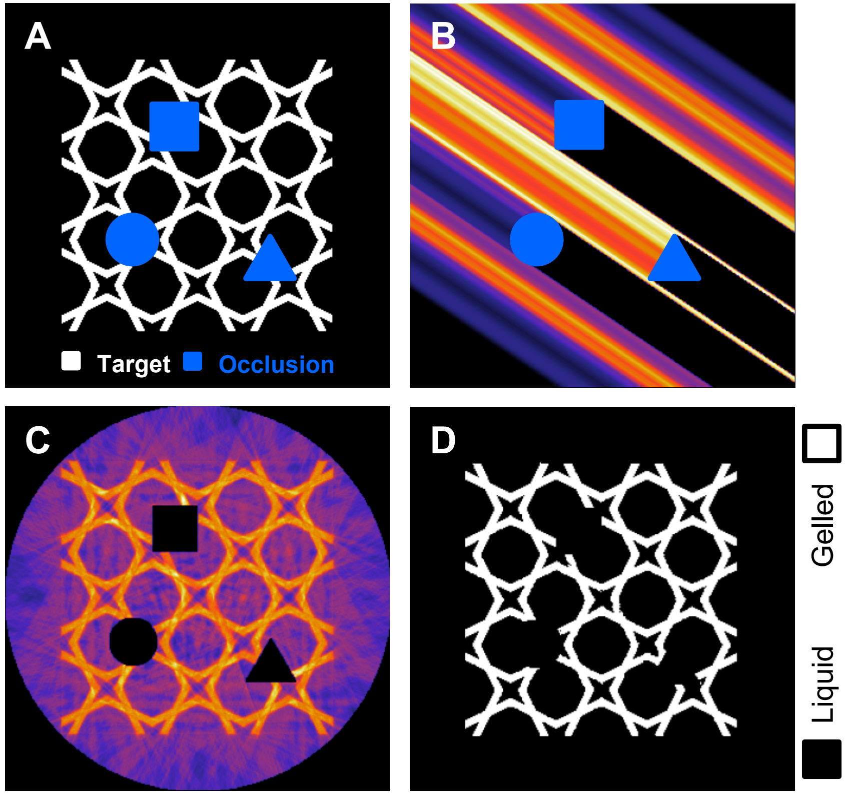
Conclusions

- All methods converge to solutions several orders of magnitude better than no optimization (FBP)
- First order methods (CAL 2019, OSMO 2021) are robust but require more iterations to converge
- High convergence rate of second order methods (PM 2021) may come at the cost of increased computational and space complexity for large 3D problems

What about more challenging physical tomographic reconstruction? — A progress survey in multimaterial tomographic VAM — overprinting

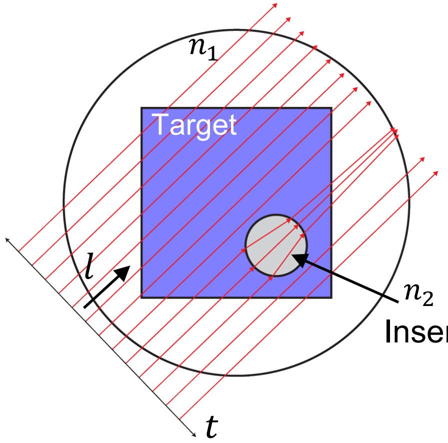
Opaque insert/occlusion





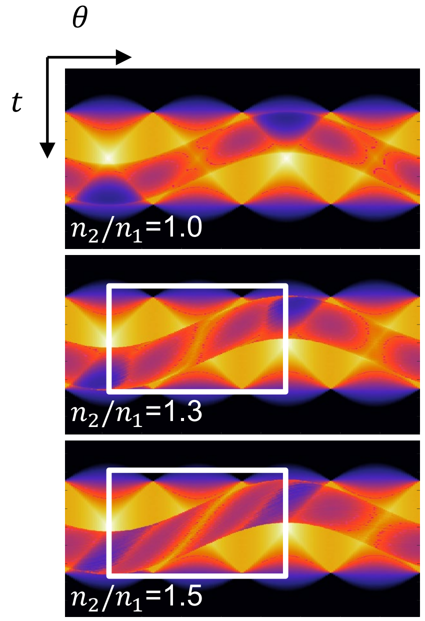
[1] C. Rackson, K. Champley, J. Toombs et al. *Additive Manufacturing*. **48**. (2021)

Transparent (refractive) insert/occlusion



[1]

$$\frac{d}{dl}\left(n\frac{dt}{dl}\right) - \frac{\partial n}{\partial t} = 0$$

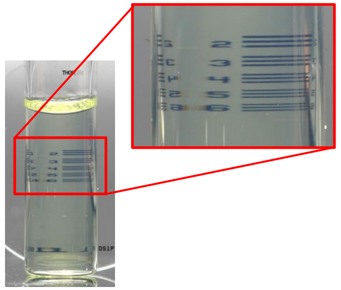


Sinogram in region affected by the refractive insert is distorted

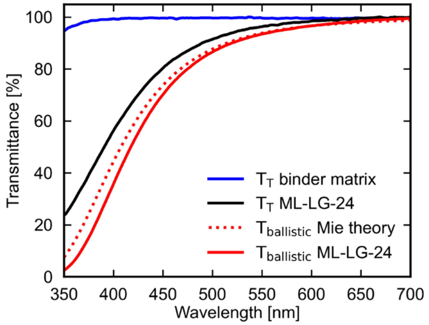
[2] Seron et al., *Comp. & Graphics*. **29**, (2005).

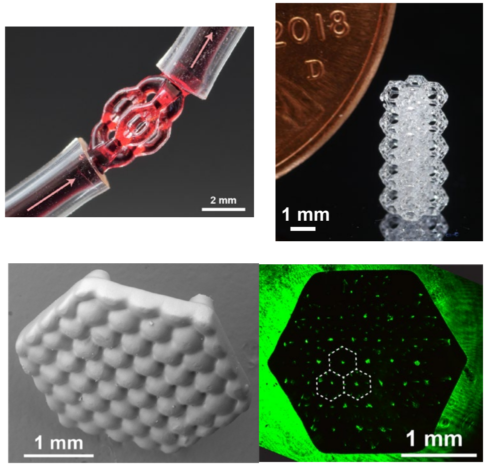
A progress survey in multimaterial tomographic VAM — scattering

$n_{particle} \approx n_{liquid}$



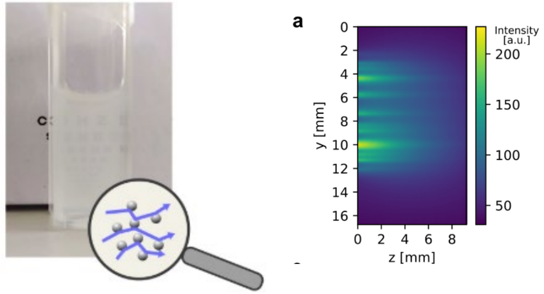
Refractive index matching $n_{silica} \approx n_{precursor}$ leads to small scattering component of total transmission

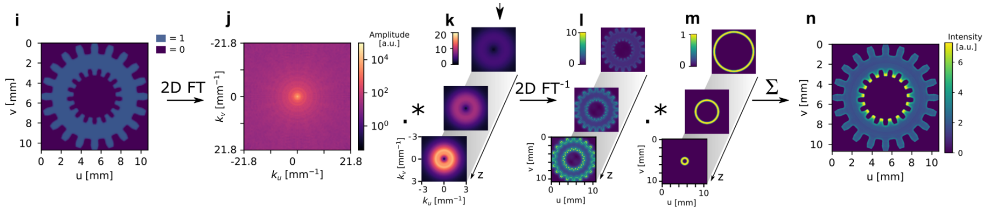




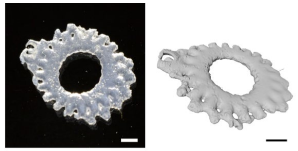
[1] J. Toombs, M. Luitz, C. Cook et al. arXiv: 2110.01651 (2021)

$n_{particle} \not\approx n_{liquid}$

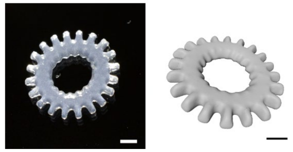




Without precompensation

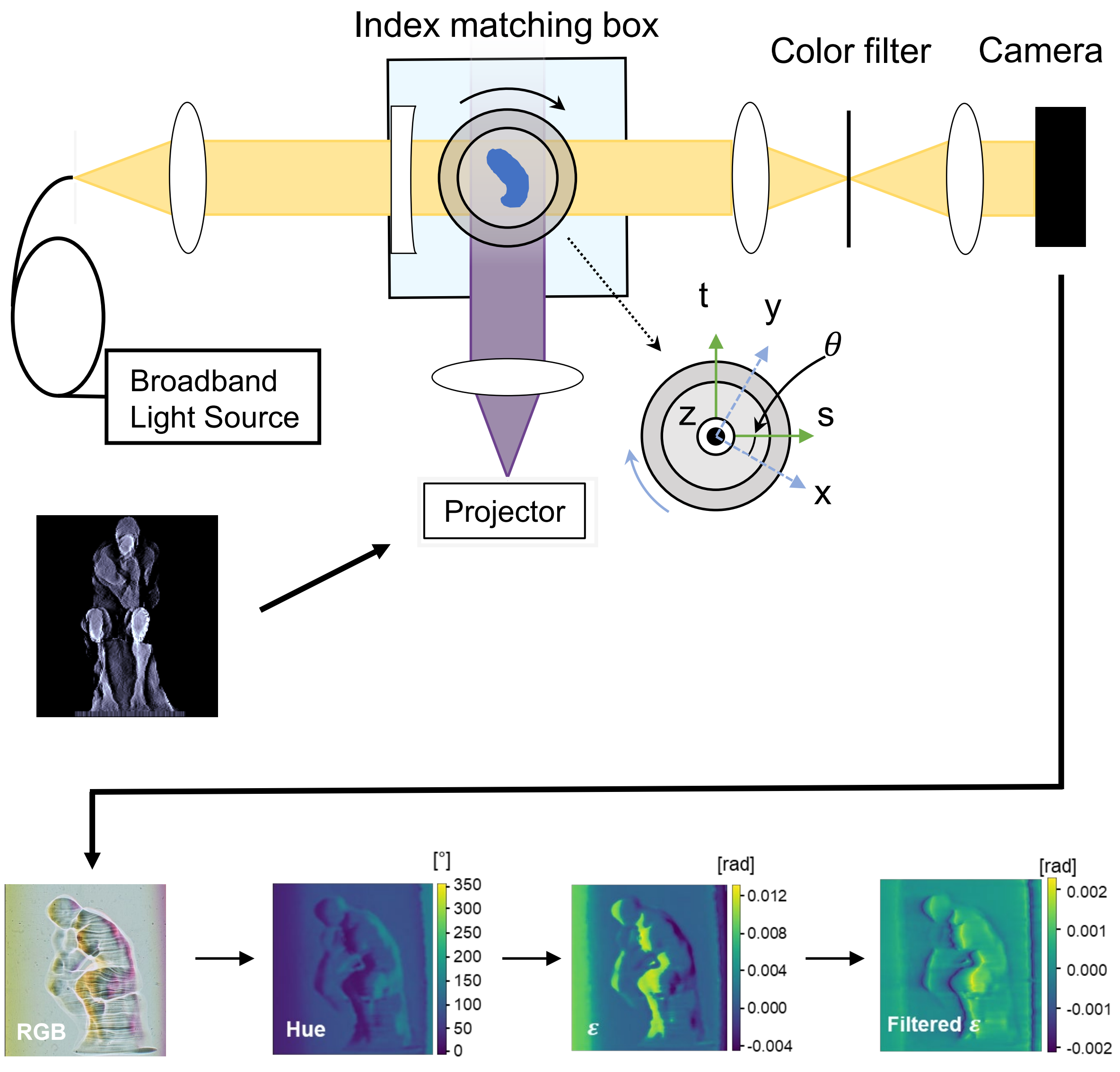


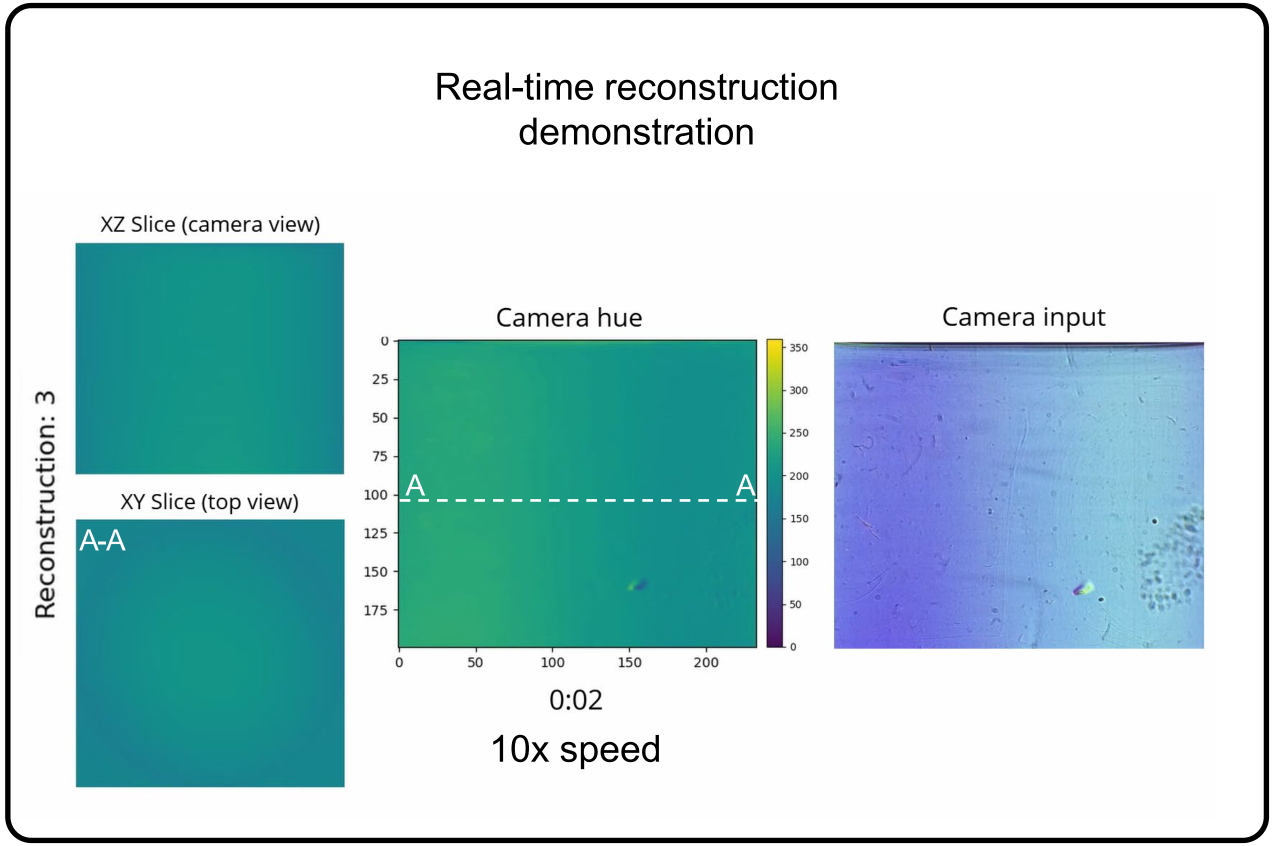
With precompensation



[2] J. Madrid-Wolff, A. Boniface, D. Loterie et al. arXiv: 2105.14952 (2021)

When modeling the physical process becomes difficult Color Schlieren Tomography paves the way to real-time monitoring and process feedback



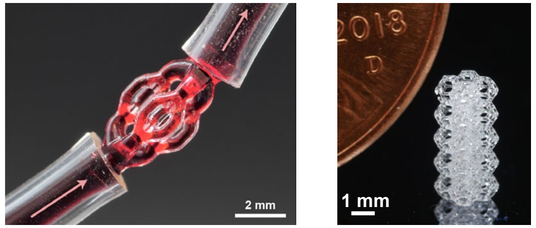


[1] C. Li, J. Toombs, H. Taylor (2021)

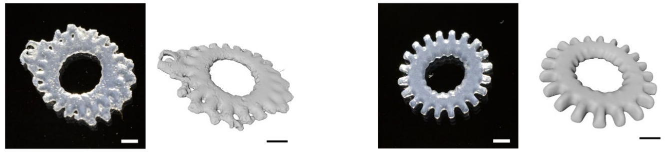
Conclusions

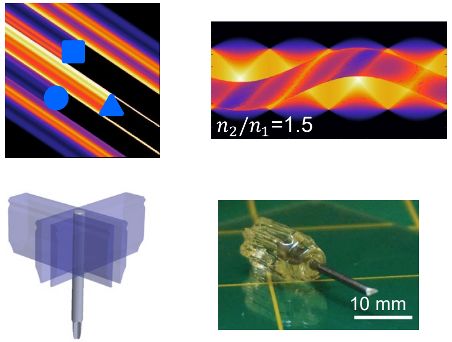
Tomographic VAM

New forward/inverse light propagation models for multimaterial printing

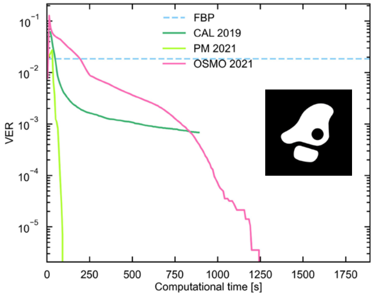


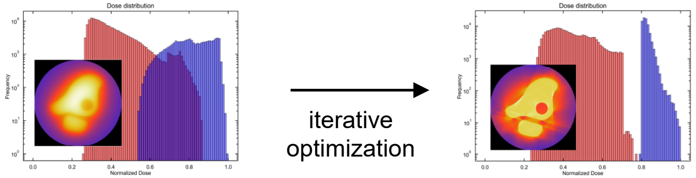
Without precompensation — With precompensation





Optimization for improved optical dose patterns





In-situ metrology/computational imaging for process feedback and monitoring