Microscale 3-D Capacitance Tomography with a CMOS Sensor Array

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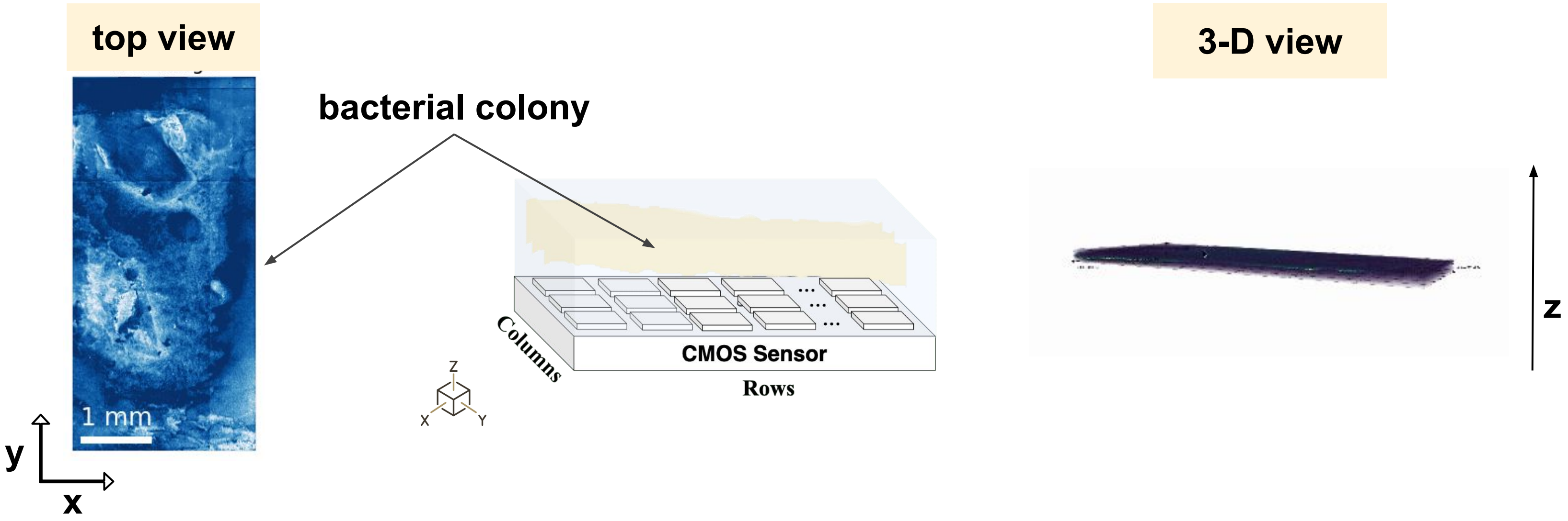
Microscale 3-D Capacitance Tomography

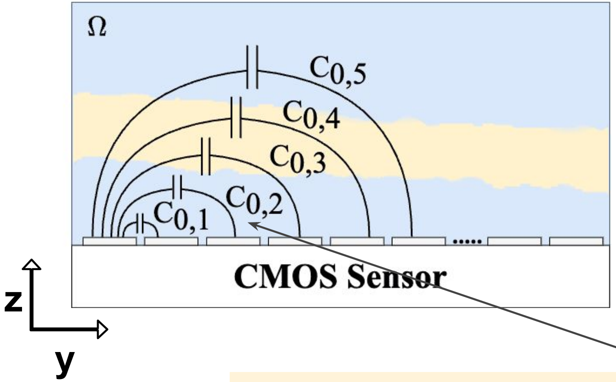
- ***Non-optical*** imaging technique for visualizing the 3-D structure of micron scale-objects like bacterial colonies using CMOS sensor arrays.



Electrical Capacitance Tomography (ECT)

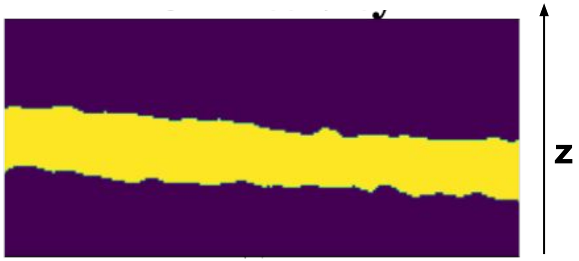
- Uses capacitance measurements to reconstruct a cross-sectional image of the area above the sensor.

1 **Measure Capacitance at the Boundary**



Solve Inverse Problem

2 **Reconstruct Cross-sectional Image**

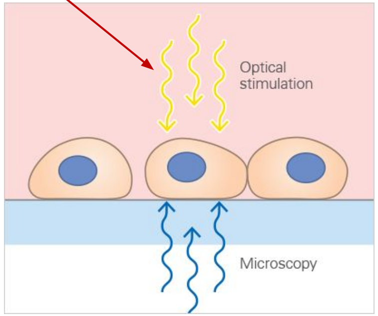


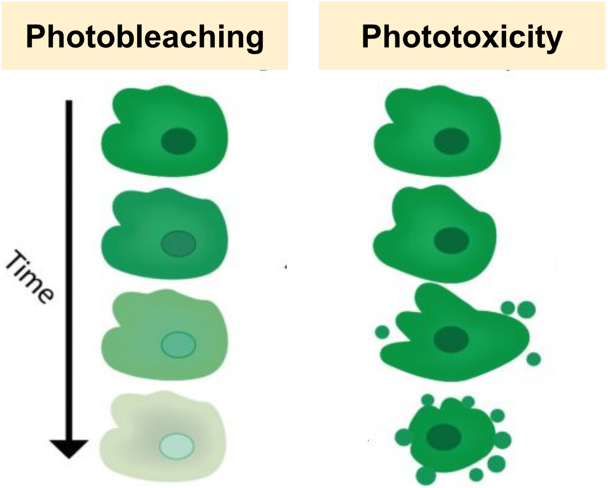
Function of the sample ***geometry***, ***thickness***, and ***dielectric properties***.

Why Microscale ECT ?

- Challenges with *optical* confocal microscopy

Intense light source



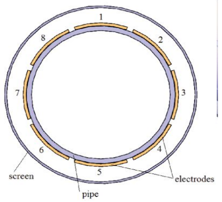


Merces, G.O.T., Reynaud, E.G. (2022). Light-Sheet Fluorescence Microscopy. In: Nechyporuk-Zloy, V. (eds) Principles of Light Microscopy: From Basic to Advanced .Springer, Cham

Capacitance Tomography Sensors

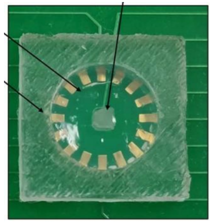
cm scale | mm scale | um scale | This Work

IEEE Sensors Journal 2018 [1]



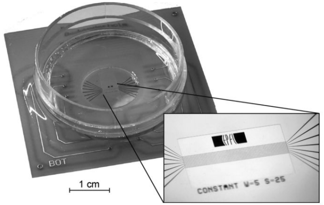
8 Electrodes

Engineering Research Express [2]



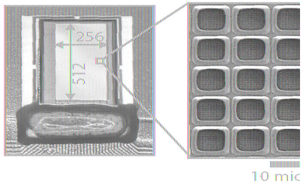
34 Electrodes
(1.4x0.8 mm²)

IEEE Transactions on Biomedical Engineering 2007 [3]



16 Electrodes
(5um x 4mm)

BioCAS 2023



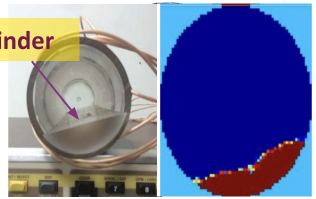
131,072 Electrodes
(10x10um²)

[1] Jin Zheng and Lihui Peng. An autoencoder-based image reconstruction for electrical capacitance tomography. IEEE Sensors Journal, 18(13):5464–5474, 2018.
[2] X. Feng Hor. Electrode configuration study for three-dimensional imaging of on-chip ect. Engineering Research Express, 5(2):025003, 2023.
[3] P. Linderholm. Cell culture imaging using microimpedance tomography. IEEE Transactions on Biomedical Engineering, 55(1):138–146, 2007.

Capacitance Tomography Sensors

cm scale | mm scale | um scale | **This Work**

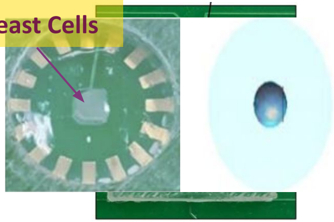
IEEE Sensors Journal 2018 [1]



8 Electrodes

Macroscopic Scale Only!

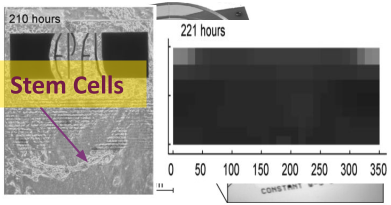
Engineering Research Express [2]



34 Electrodes (1.4x0.8 mm²)

Can't resolve fine features

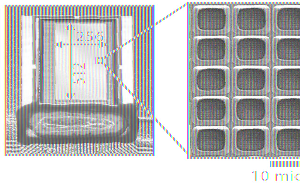
IEEE Transactions on Biomedical Engineering 2007 [3]



16 Electrodes (5um x 4mm)

Can't resolve fine features

BioCAS 2023



131,072 Electrodes (10x10um²)

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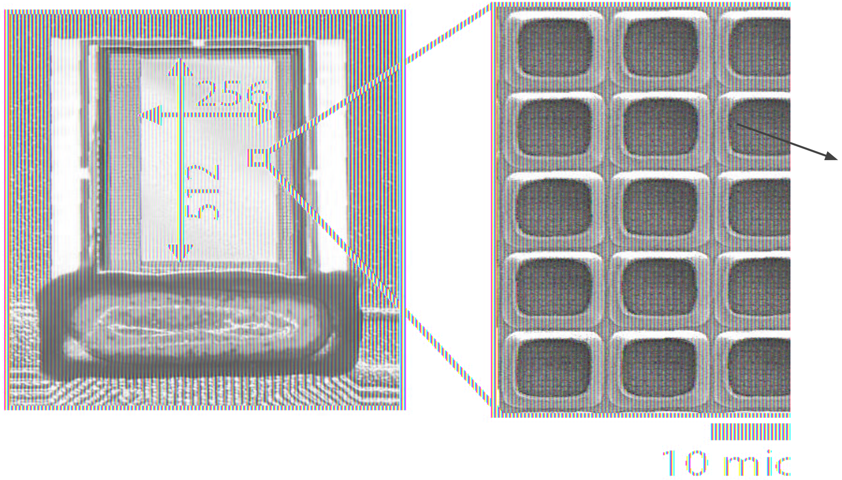
[3] P. Linderholm. Cell culture imaging using microimpedance tomography. IEEE Transactions on Biomedical Engineering, 55(1):138–146, 2007.

Capacitance Tomography Hardware

- **512x256 CMOS Sensor (131,072** sensing electrodes)

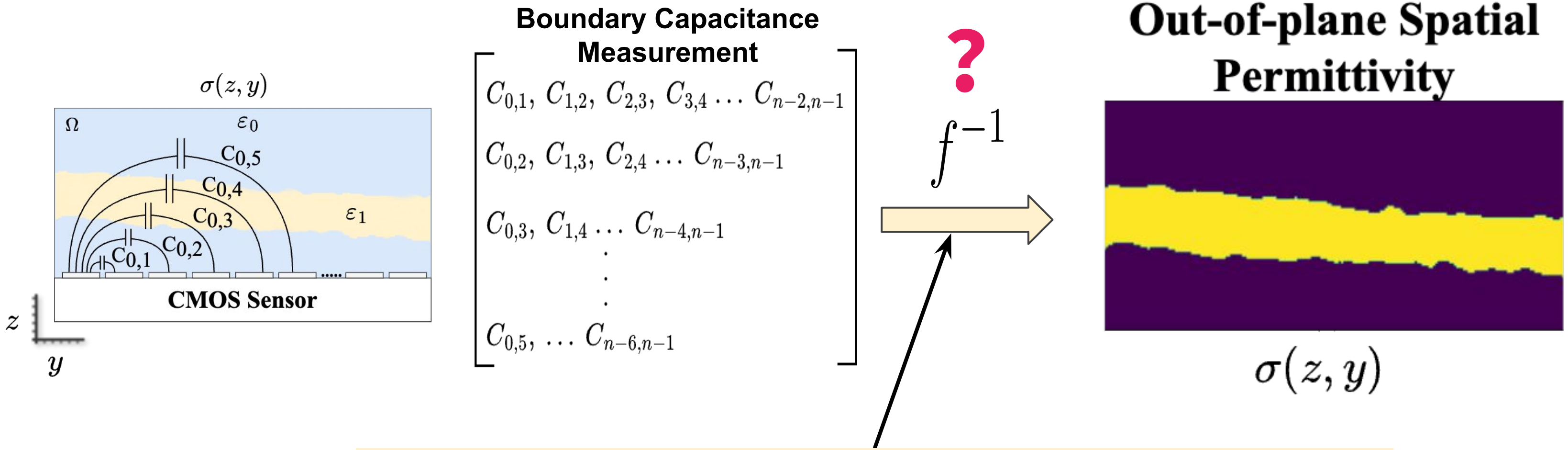


Electrodes on a 10 um grid

Sensor can measure capacitance between any two electrodes in the array

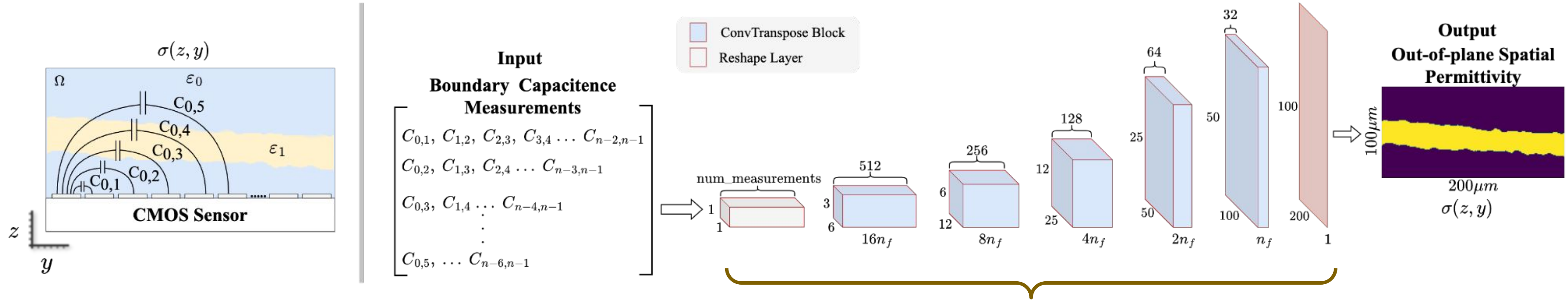
K. Hu, J. Ho and J. K. Rosenstein, "Super-Resolution Electrochemical Impedance Imaging With a 512 × 256 CMOS Sensor Array," in *IEEE Transactions on Biomedical Circuits and Systems*, vol. 16, no. 4, pp. 502-510, Aug. 2022, doi: 10.1109/TBCAS.2022.3183856.
* We thank P. Joshi for assistance with electron microscopy

Capacitance Measurement → Cross-sectional Image



Approximate the inverse function f^{-1} using deep learning

Image Reconstruction Using Deep Learning

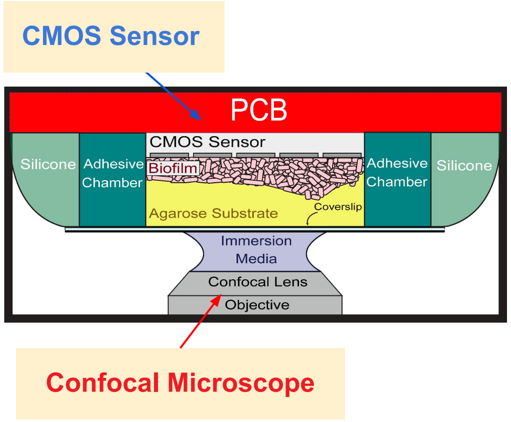


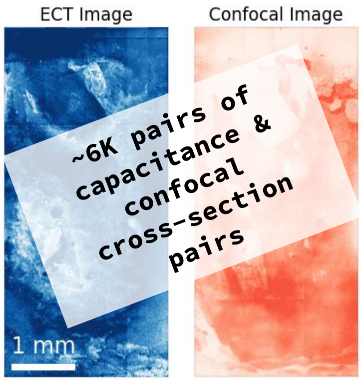
Approximation to f^{-1}

Training Data

1 **Experimental Dataset**

- Imaging the same sample using CMOS sensor and a confocal microscope:
  - CMOS Sensor → Boundary capacitance measurements
  - Confocal Microscope → 3-D Shape of the sample





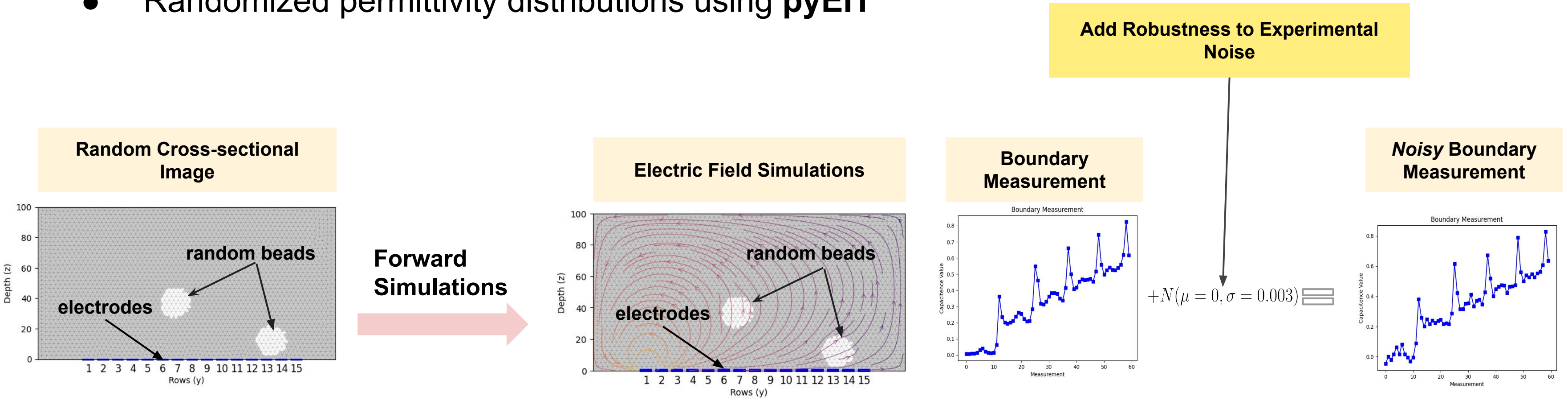
Biofilm Dataset

Microsphere Dataset

Training Data

2 Synthetic Dataset

- Randomized permittivity distributions using **pyEIT***

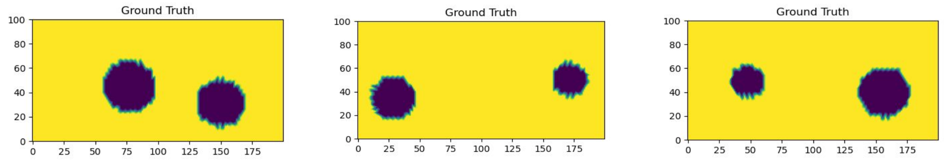
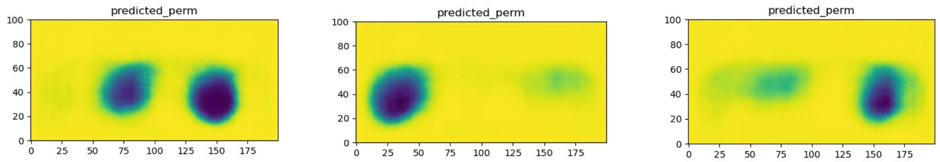


*Benyuan Liu, et al. pyeit: A python based framework for electrical impedance tomography. SoftwareX, 7:304-308, 2018.

Loss Function

- **Class Imbalance:** foreground pixels occupy a smaller region compared to background pixels.

- MSE Loss produces **blurred/smeared** predictions due to to the class imbalance issue.

Simulated Cross-sectional Images from pyEIT*	
Predictions with MSE Loss	

*Benyuan Liu, et al. pyeit: A python based framework for electrical impedance tomography. SoftwareX, 7:304–308, 2018.

Loss Function

- Use compound loss function to address the class-imbalance issue

$$L(y, \hat{y}) = \lambda_1 L_{\text{SmoothL1}}(y, \hat{y}) + \lambda_2 L_{\text{FL}}(y, \hat{y}) + \lambda_3 L_{\text{Dice}}(y, \hat{y})$$

Per-pixel Loss

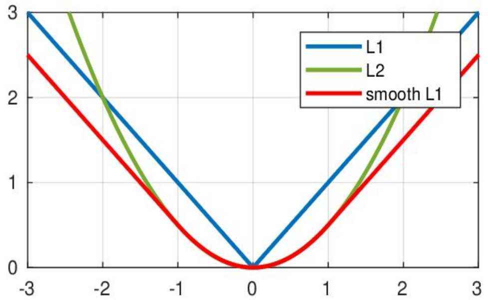


Figure from 10.1109/CVPR.2018.00238

Focal Loss
Distribution-based Loss

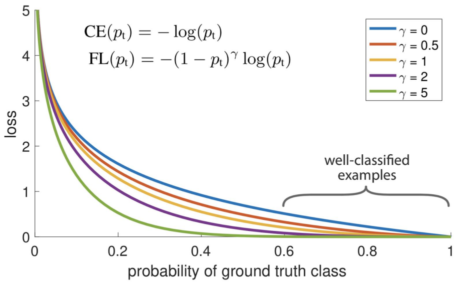


Figure from 10.1109/CVPR.2018.00238

Region-based Loss

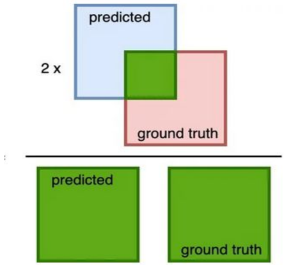


Figure from https://i.stack.imgur.com/OsH4y.png

Experimental Results on Testing Datasets

ECT Imaging of:

- ➔ Polystyrene Microspheres (*20μm* diameter)
- ➔ Bacterial Biofilm (*B. subtilis*)

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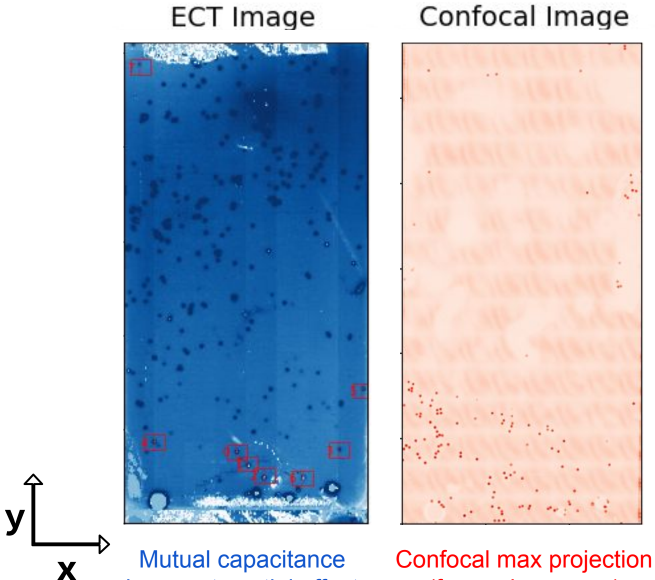
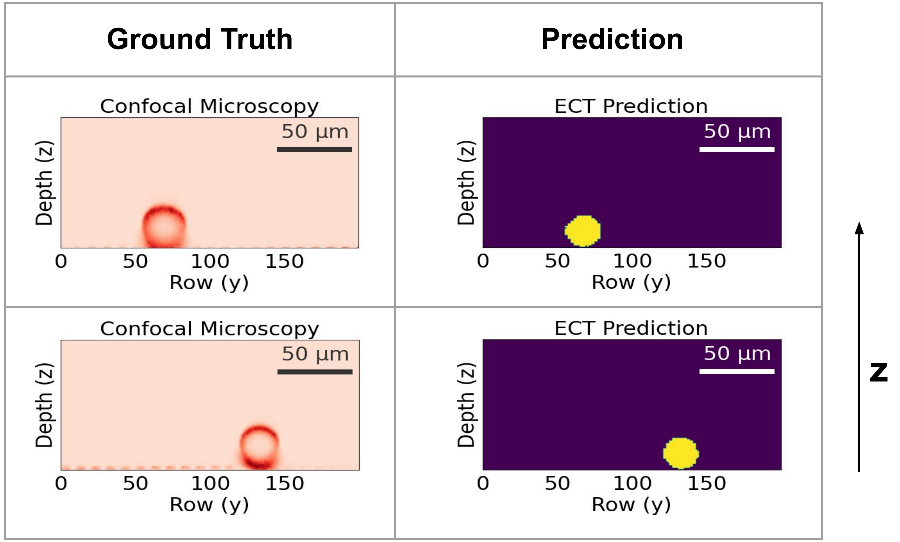
Experimental Results: Polymer Microspheres

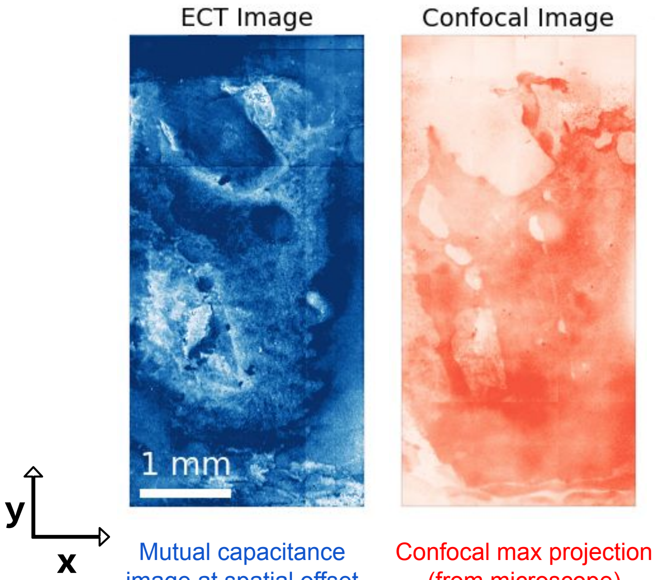


Mutual capacitance image at spatial offset 1 (from CMOS)

Confocal max projection (from microscope)

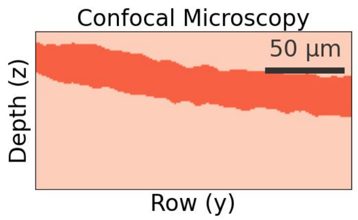
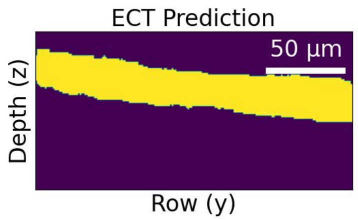
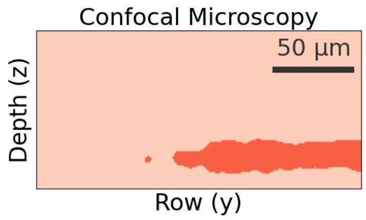
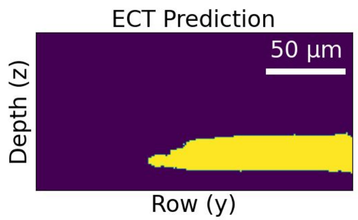
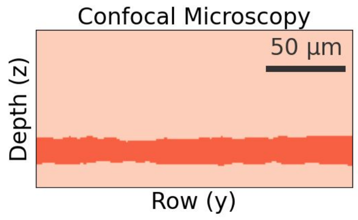
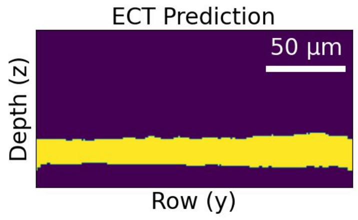


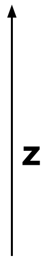
Experimental Results: Polymer Microspheres



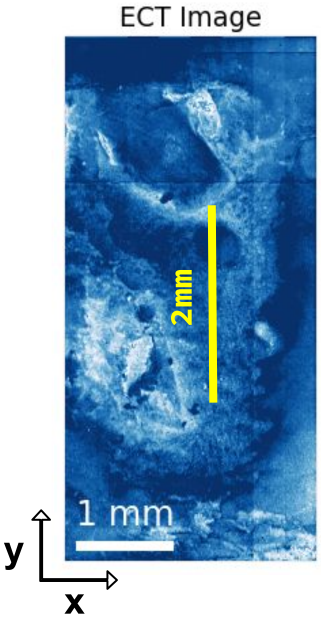
Mutual capacitance image at spatial offset 1 (from CMOS)

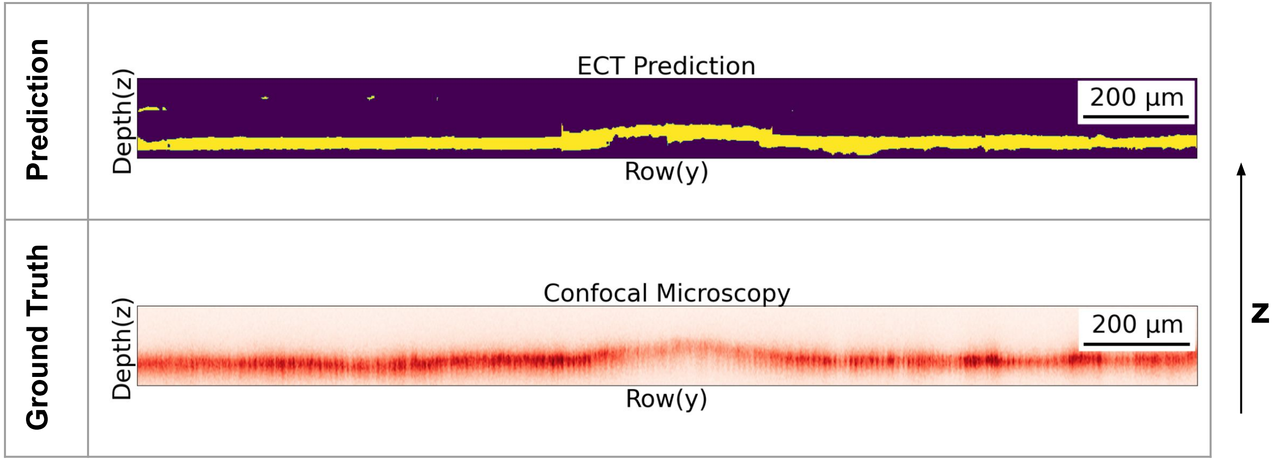
Confocal max projection (from microscope)

Prediction	Ground Truth
	
	
	

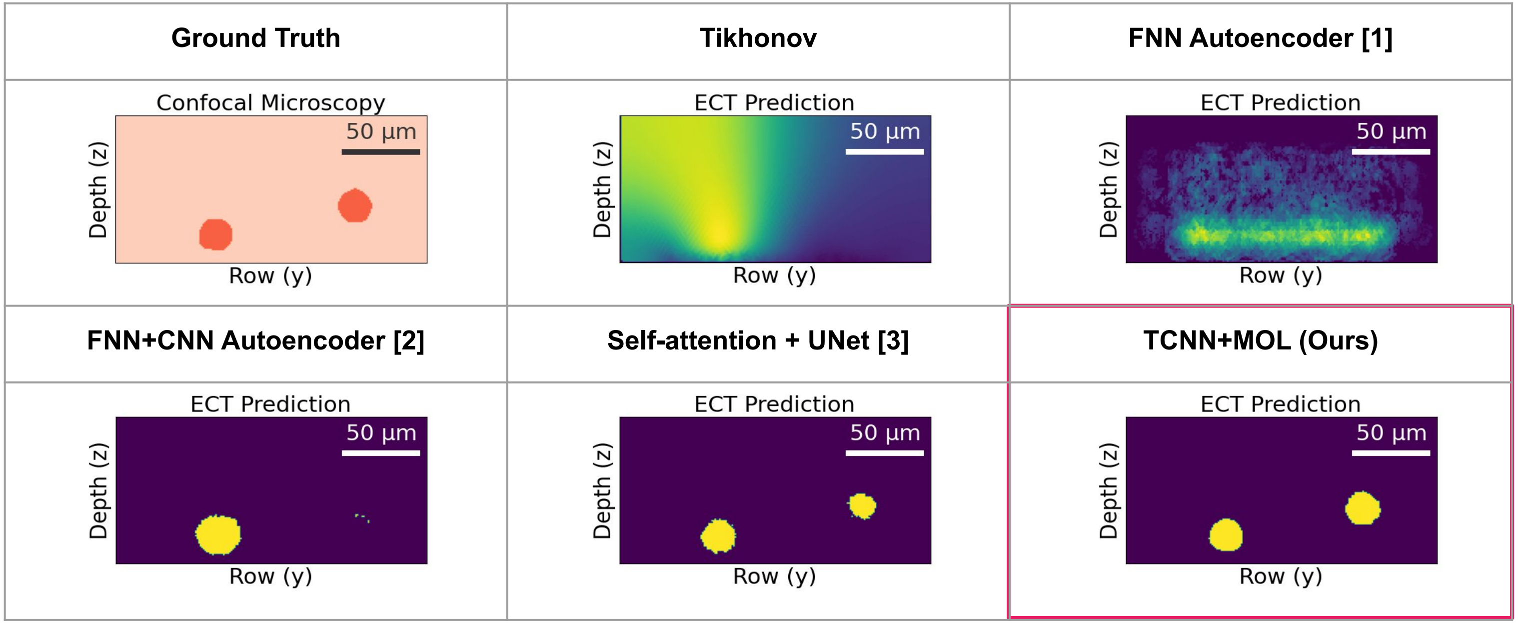


Experimental Results: Large Scale Cross-Section





Experimental Results: Reconstruction Quality



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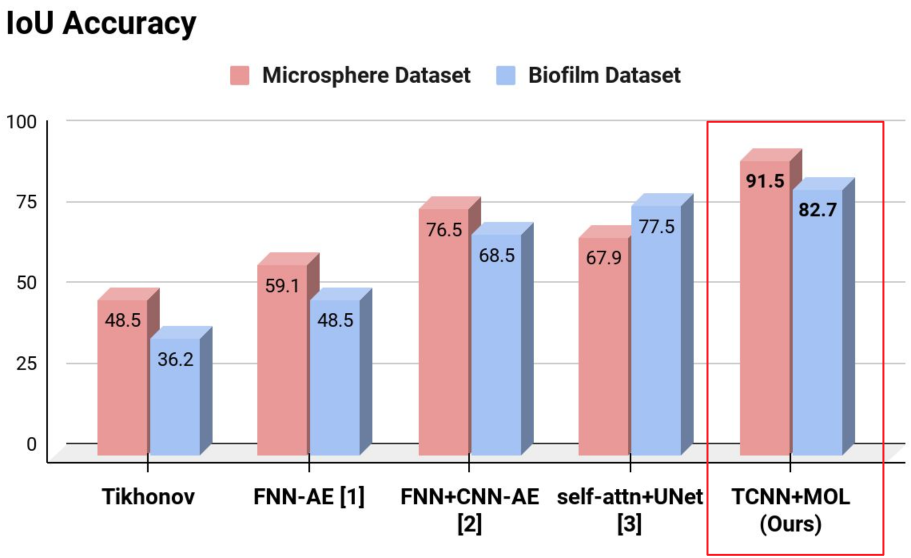
[2] Hai Zhu, Jiangtao Sun, Lijun Xu, Wenbin Tian, and Shijie Sun. Permittivity reconstruction in electrical capacitance tomography based on visual representation of deep neural network. IEEE Sensors Journal, 20(9):4803–4815, 2020.
[3] Gao Xinxin, Tian Zenan, Qiu Limin, and Zhang Xiaobin. A hybrid deep learning model for ect image reconstruction of cryogenic fluids. Flow Measurement and Instrumentation, 87:102228, 2022.

Experimental Results: Reconstruction Quality



➔ **Microsphere Dataset (Ω_1): 91.5%**

➔ **Biofilm Dataset (Ω_2): 82.7%**

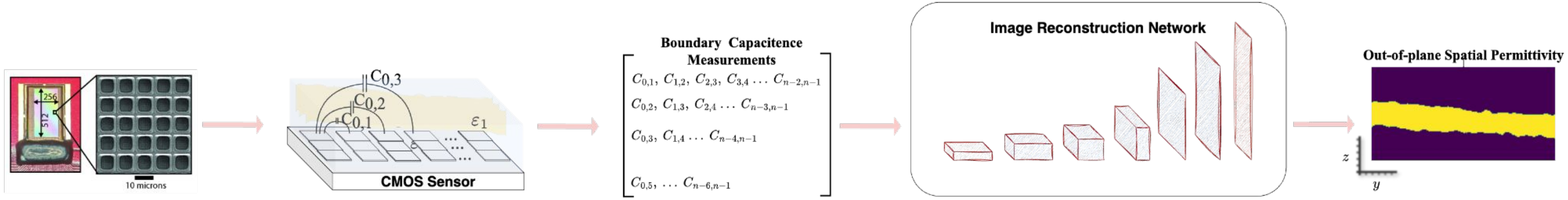
[1] Jin Zheng and Lihui Peng. An autoencoder-based image reconstruction for electrical capacitance tomography. IEEE Sensors Journal, 18(13):5464–5474, 2018.
[2] Hai Zhu, Jiangtao Sun, Lijun Xu, Wenbin Tian, and Shijie Sun. Permittivity reconstruction in electrical capacitance tomography based on visual representation of deep neural network. IEEE Sensors Journal, 20(9):4803–4815, 2020.
[3] Gao Xinxin, Tian Zenan, Qiu Limin, and Zhang Xiaobin. A hybrid deep learning model for ect image reconstruction of cryogenic fluids. Flow Measurement and Instrumentation, 87:102228, 2022.

Conclusion

➔ Microscale ECT has the potential to provide **low cost non-optical** 3-D monitoring of cell cultures.

- Highest ECT resolution 10μ & largest field of view (131,072 sensing electrodes) reported to date.

➔ Deep Learning algorithms can provide accurate image reconstructions. This has been demonstrated on two experimental datasets: polymer microspheres and bacterial biofilms.



Acknowledgments - HyBISCIS Team

Joseph Incandela, Kangping Hu, Pushkaraj Joshi, Xiaoyu Lian, Yutong Wu, Gabriel Monteiro Da Silva

Joseph W. Larkin, Sherief Reda, Christopher Rose, Brenda Rubenstein, Jacob Rosenstein

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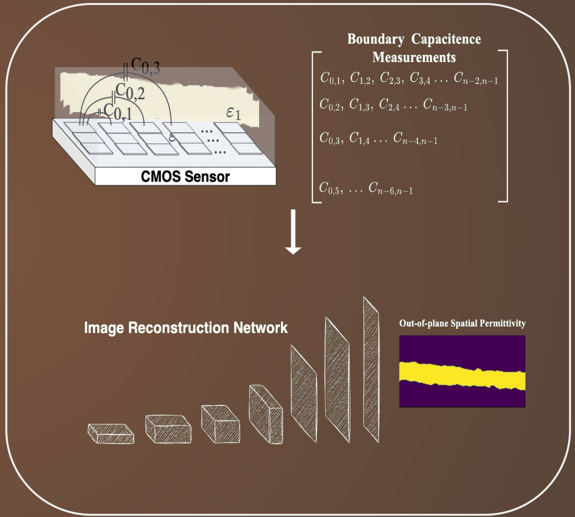

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