Adaptive Electrical Capacitance Volume Tomography for Real-Time Measurement of Solids Circulation Rate at High Temperatures

**PI:** Qussai Marashdeh, Tech4Imaging LLC

**OSU Team:** Professor Fernando Teixeira and Graduate Students
Introduction

• Adaptive Electrical Capacitance Volume Tomography (AECVT) is a 3D imaging technique for Multi-phase flow measurement.
• AECVT offers substantially higher imaging resolution compared to the conventional ECVT
• New image reconstruction algorithms are developed to exploit increase in measurements using AECVT sensors.
• An AECVT system and sensor is being developed as part of this SBIR Phase II effort.
AECVT Motivation: Two Sphere Experiment
Irregular Shape Experiment

12 channel Sensor

3D Concentration map

Axial Cross-sectional maps

24 channel Sensor

3D Concentration map

Axial Cross-sectional maps
Gas-Solid Experiment
Adaptive and conventional plates in 2D depiction

**Conventional Plate**

**Adaptive Plate:** Each segment is activated with different levels of amplitude and phase

Excitation Implementation
Space Adaptive Excitation and Reconstruction
Axial Excitation

1x3 Axial Segment

3x3 Axial Electrode 01
3x3 Axial Electrode 02
3x3 Axial Electrode 03

3x3 Axial Electrode
Azimuthal Excitation
Singular Value Markers

SVD Analysis of Sensor Inner Domain

Singular value $\lambda_i$ vs. singular value index $i$

Markers: G (Green), R (Red), B (Blue)

Legend:
- 0.2R 3 x 3 Axial
- 0.4R 3 x 3 Axial
- 0.8R 3 x 3 Axial
- 0.2R 3 x 3 Azimuth
- 0.4R 3 x 3 Azimuth
- 0.8R 3 x 3 Azimuth
- 0.2R ECVT
- 0.4R ECVT
- 0.8R ECVT
**Space Adaptive Reconstruction Technique**

| Basics of two-step SART: (a) Step 1, where acquisition mode 1 is used to image the periphery region indicated in white color. (b) Step 2, where acquisition mode 2 is used to image the center region in white color using the reconstruction results of Step 1 in red color as input (a priori) data. Multiple steps, involving more than two spatial regions, can also be employed. |
Singular Value Markers

**Step 1.** The permittivity reconstruction of the outer shell region $R_1$ can be done by employing LBP (for example) and acquisition mode 1, shown in Fig. (a), so that

$$
\begin{bmatrix}
g_1^{(1)}(x) \\
\end{bmatrix}_{M_1 \times 1} =
\begin{bmatrix}
s_1^{(1)}(x) \\
\end{bmatrix}^T_{M_1 \times P_1} 
\begin{bmatrix}
C_1(x) \\
\end{bmatrix}_{P_1 \times 1}
$$

**Step 2.** The permittivity reconstruction of the center region $R_2$ can be achieved by employing the LBP method and by using the reconstructed permittivity profile of $R_1$ region found in Step 1 as a (input) background permittivity in the forward solver together with acquisition mode 2, shown in Fig. (b). Assuming again LBP reconstruction, this can be expressed as

$$
\begin{bmatrix}
g_2^{(1)}(x) \\
\end{bmatrix}_{M_2 \times 1} =
\begin{bmatrix}
s_2^{(1)}(x) \\
\end{bmatrix}^T_{M_2 \times P_2} 
\begin{bmatrix}
C_2(x) \\
\end{bmatrix}_{P_2 \times 1}
$$

**Step 3.** After step 1 and step 2, the first iteration of SART is completed with reconstructed permittivity profiles for regions $R_1$ and $R_2$, denoted as $g_1^{(1)}$ and $g_2^{(1)}$, respectively. A residual error functional is next evaluated in order to determine the quality of reconstructed permittivity profile as:

$$
RRE = \frac{\sum_{i=1}^{P_1} |C_i - C_1^{(j)}|}{\sum_{i=1}^{P_1} |C_i|}
$$
Sensor Design

Dead Zones


SART implementation

- Inner Resolution
- Large Segment
- Small Segment
- Outer Resolution
- Inner Resolution
SART implementation

(a) Imaging setup of a ring-shaped object, located at $r=0.85m$ and with thickness is $0.2m$, with 36 capacitor plate segments, where the plates are placed around in a 1 m radius circle around the imaging domain with $2^\circ$ separation between each plate. (b) Simulation setup for the same ring object with 12 synthetic plates composed of 3 segments each. (c) Image reconstruction result for case (a). (d) Image reconstruction result for simulation case (b).
Example
Sensor Geometry and Singular values

Farthest plates

Closest Plates
Sensor Design

Cylindrical
216 segments
Modular Acquisition
Variable voltage excitation
Programmable voltage patterns
Activation Scheme

Select Activations

Processor 1

SART Algorithm

Channel selection algorithm

Image viewing

Data analysis

Control Signals

Processor 2 (FPGA)

Receiver Balance

Adder

Op-Amp

PGA

ADC

Detector Reference

90° Phase Shifter

Digital Root-Sum-Square

Digital Multipliers

Digital LPF's

USB

Capacitance Measurements

Digital Blocks and DDS are inside FPGA

Detector Reference

90° Phase Shifter

Digital Root-Sum-Square

Digital Multipliers

Digital LPF's

USB
## Phase II Schedule

**Task 1:** Electrical design of AECVT sensor for high temperatures  
**Task 2:** ECVT sensor mechanical design for high temperatures  
**Task 3:** ECVT sensor fabrication  
**Task 4:** Build test chamber  
**Task 5:** Data Acquisition System (DAS) firmware and electronic design  
**Task 6:** Testing  
**Task 7:** Implement image reconstruction algorithm based on developed SART technique  
**Task 8:** Develop feature extraction  
**Task 9:** System integration and testing in real-time  
**Task 10:** Software interface  
**Task 11:** Finalize demonstration unit

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Phase II Milestones

**Year 1 Milestones:**

1. Finalize AECVT sensor design - end of 2nd quarter.
2. Development of software for SART reconstruction technique - end of 4th quarter.
3. Fabrication of adaptive data acquisition system - end of 5th quarter.

**Year 2 Milestones:**

1. Fabrication of AECVT sensor - end of 5th quarter.
2. Finalize image reconstruction and feature extraction - end of 7th quarter.
3. Demonstrate integrated system - end of 7th quarter.
4. Finalize GUI - end of project.
5. Finalize demonstration unit and develop virtual experience - end of project.
Conclusion

• Higher ECVT resolution is directly proportional to increased number of plates.
• Adaptive ECVT (AECVT) is based on substantial increase in number of synthetic plates using plate segmentation.
• Adaptive ECVT is a new technology at the frontier of higher resolution capacitance imaging:
  – Infinite options of plate arrangements and independent number of measurements
  – Maintain High SNR of acquired measurements
  – Ability to beam ECVT resolution toward a desired region
  – Ability to Zoom ECVT resolution toward a desired region
• Feasibility of AECVT was established in Phase I effort.
• In this Phase II, realization of a full AECVT system for high resolution solid mass flow gauging will be realized.