Electric Potential and Electric Field Imaging with Dynamic Applications

2017 Research Award for Innovation

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Background

• NDE historically has focused technology development in propagating wave phenomena:
  • X-ray, ultrasonic, microwave, thermal, terahertz, and eddy current
  • Little attention to the field of electrostatics and emanating electric fields.

• Interest in evaluating the integrity of wire insulation in aircraft and aerospace systems

• This work is based on the original electric field sensor (e-Sensor) work disclosed by Generazio (2002).
Electric Potential and Electric Field Imaging with Applications

e-Sensor Array Based on Field Effect Transistors

Resistance load

Each gate (G) is a measurement electrode

To data acquisition system
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Floating gate design
Dielectric constant, relative permittivity, $\varepsilon$

Electric susceptibility, $\chi = 1 - \varepsilon$

$\varepsilon = 1$ vacuum
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Human Hands
Asbestos
Rabbit Fur
Glass, Mica
Human Hair
Nylon, Wool
Lead
Silk
Aluminum
Paper
Cotton
Steel
Wood
Amber
Hard Rubber
Mylar
Nickel, Copper
Silver, Brass
Gold, Platinum
Polyester, Celluloid
Saran Wrap
Polyurethane
Polypropylene
Vinyl, Silicon
Teflon
Silicon Rubber

POSITIVE charge

NEGATIVE charge

Triboelectric affinity

+ NEUTRAL -
Electric Potential and Electric Field Imaging with Applications

- Low dielectric constant/Low electric susceptibility
- Non-conductor
- Neutral triboelectric affinity
Catch 22

- Want to select the best materials for constructing an electric field measurement system, however, the actual electrical properties vary or are unknown in configuration to be used.

- Insulation on wiring
- Wire diameters
- Circuit elements
- Support materials

- Don’t know actual electrical properties until tested
An Example, “e - Sensor” Antenna Configuration for Wiring Inspection

New Insulation

Damaged Insulation

Electrical equipotential surfaces \((V_1, V_2, V_3, V_4)\) are distorted due to damaged or aged insulation. Some antenna elements are no longer parallel to the electrical equipotential surfaces and now are exposed to an increase in potential.

The electric field, \(\mathbf{E}\), at any point is given by \(-\nabla V = \mathbf{E}\), where \(V\) is the electrical potential.
“e - Sensor” Data from Prototype

Wire passing through e - Sensor prototype

e - Sensor

e - Sensor LEDs are dimmed proportionately by the presence of the spatially varying electric potential existing around statically charged insulated wire.
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2nd Prototype
Electric Potential and Electric Field Imaging with Applications
Electric Potential and Electric Field Imaging with Applications
Voltage Response from 16 e-Sensors

Dipole Rotation Rate = 120 RPM
Quasi-static Electric Field Frequency = 2 Hz

Volts

Acquisition point

Time (sec)
Ed Generazio’s

1st electric field image of a human, 10/23/2012

Electrical potential image of a human in a uniform electric field

• First images identify rich areas of improvement.
• Imaging volumetric dielectric properties of structures
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![Image of objects with dimensions 15.24 cm.](image1)

- **Front**
- **Back**

#### Electric Potential

- **a.**

#### Electric Potential 3D

- **b.**
- **c.**
- **d.**

#### Electric Potential 3D 45°
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\[ E(x_i, y_i, z_i) \approx -\frac{V(x_{i+1}, y_i, z_i) - V(x_i, y_i, z_i)}{x_{i+1} - x_i} \hat{i} + \frac{V(x_i, y_{i+1}, z_i) - V(x_i, y_i, z_i)}{y_{i+1} - y_i} \hat{j} + \frac{V(x_i, y_i, z_{i+1}) - V(x_i, y_i, z_i)}{z_{i+1} - z_i} \hat{k} \]
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Representation of Cable Showing Cable Orientation RG-174/U 50 OHM Cable 0.256 cm Outer Jacket Diameter

Electrostatic potential distortion around a cable carrying no current.
Electrostatic potential distortions have extremely large spatial distributions compared to cable diameters.
The electrostatic potential ranges from -3 volts (lightest areas) to -2 volts (darkest areas).

Image of actual electrostatic potential distortion around LM324 Operational Amplifier (LM324 DIP), 10 mm x 20 mm top surface is normal to reference electric field.
Electrostatic potential distortions have extremely large spatial distributions compared to amplifier dimensions.
The electrostatic potential ranges from -3 volts (darkest areas) to -4 volts (lightest areas).

LM324 DIP OP AMP Location

200 mm

100 cm
Electric Potential Image
Electric Potential and Electric Field Imaging with Applications

Electric Potential Images

As received rods

60.96 cm

Silk cloth passed over surface

<table>
<thead>
<tr>
<th>Dielectric Constant</th>
<th>Triboelectric Affinity</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0 – 2.1</td>
<td>PTFE</td>
</tr>
<tr>
<td>2.7</td>
<td>Acrylic</td>
</tr>
<tr>
<td>1.2 – 2.1</td>
<td>Wood</td>
</tr>
<tr>
<td>3</td>
<td>Nylon</td>
</tr>
<tr>
<td>5 – 5</td>
<td>Garolite</td>
</tr>
<tr>
<td>4 - 9</td>
<td>Mica ceramic</td>
</tr>
<tr>
<td>3.8</td>
<td>Borosilicate Glass</td>
</tr>
<tr>
<td>2.8 - 4.1</td>
<td>Polyester</td>
</tr>
</tbody>
</table>

Samples are in order left to right
Electric Potential and Electric Field Imaging with Applications

EFI: New Electrostatic Eyes

PTFE Panel
Wood Frame

EFI Electrostatic Potential Image of latent charge distribution generated by triboelectrically drawing the letters "NASA" on PTFE. The EFI image is overlaid onto the area scanned.

Electric Potential Image

PTFE, Teflon Panel

6.35 mm x 30.38 cm x 30.38 cm

The letter "N" triboelectrically hand drawn on the front (upper) and back (lower) of a PTFE panel.
Characterization by Charge Tunneling, Injection, and Distribution
Figure 1

Non-conducting container

Container wall, outside surface

Container wall, inside surface

Initial Polarization Due to Bound and Unbound Charges at $\tau = 0.0$

Residual Charge Due to Charge Buildup at $\tau_1 = \tau + \Delta \tau > 0.0$

Initial Displacement Fields Due to Bound Surface Charges at $\tau = 0.0$

Figures a, b, c, and d illustrate the various fields and charges under different conditions.
e-Sensor data write test bed system – identifying organic memory parameters

(a) Array support
(b) Electrode
(c) Storage Panel
(d) Adjustable Height Electrode supports

Potential Control Resistors
Conducting strips
Electrode wires
Array support
Adjustable Height Electrode supports
Array support
Hinges
Data Storage Panel
Electrode
Data Storage Panel
Ed Generazio February 8, 2015
After Erasure McMaster Label on back side reveals new inspection technology for hidden objects.

Data writes without using a triboelectric process

Electric Potential Images
Electric Potential and Electric Field Imaging with Applications

Optical image of container

Optical image of ABS gun in container

Packing material

ABS gun simulator inside

Electric potential image of container

Electric potential of gun
Foot Prints on Static Protection Office Rug

Footfalls are outlined in dashed curves

1.219 m

27.94 cm

Optical Image of Rug Surface

EFI Image (electrical potential)

Optical Image of Bottom of Right Shoe

5 minutes

$\Delta V = -4.46$ Volts
Very conservative sensitivity at 1.55mV/cm

Several orders of magnitude by FET selection, components, filtering, structural design, etc.
Ephemeral e-Sensor
True Electric Potential Measurements are Made When Sensor is in Quasi-static Motion

Sampled voltage from ephemeral sensor at equilibrium electrical potential

2.4 Hz

Trigger signal for sampling electric potential at a fixed rotational position

Sample potential at negative edges of trigger signal

2.4 Hz
Typical Measured Ephemeral Sensor Response in the Presence of a Charged Axially Symmetric Object

Non-rotating sensor

Equilibrium electrical potential

Position on X-Axis

Rotating sensor

Equilibrium electrical potential

Position on X-Axis
Solid State
Ephemeral e-Sensor
Solid State Ephemeral Sensor, ergFET
n-Channel JFET Based ergFET

with Equilibrium Pump and Quasi-static Direct Potential Controls

resistance

ergFET

Drain

Gate

Source

Equilibrium pump electrode

V_{FEPC, external}

S_1

Feedback equilibrium pump control

Additional controls

V_{p, external}

S_2

V_p, feedback

V_{QSDP, external}

S_4

NC (internal)

V_0

V_0(\tau)

S_3

V_s

V_s(\tau)

Quasi-static direct potential control
Cylindrically Symmetric Charged Object

ergFET Sensor

- X

Z-axis

Non-ergFET Sensor

\[ Z_1 \]

\[ Z_2 \]
Solid State ergFET e-Sensor Response

No Charged Object Present
Quasi-Static Power Supply @ 3 Hz, 0.0 to +9 V
Equilibrium Pump +9 V

V_{out}

0

Time

Cylindrically Symmetric Charged Object Present
Quasi-Static Power Supply @ 3 Hz, 0.0 to +9 V
Equilibrium Pump +9V

V_{out}

0

Erroneous Asymmetric Electrostatic Potential and Image Representation

- Non-ergFET Sensor
- Equilibrium Potential
- Leakage Effect
- Equilibrium Potential
- ergFET Sensor

Position on X-Axis

X-Axis

ermFET Yields Symmetric Electrostatic Potential and Image Representation
$V_{\text{pump}}, \text{Equilibrium Pump Voltage (Volts)}$

No Charged Object

100 mSec

Charged Object at a Distance $Z_1$ from ergFET

Charged Object at a Distance $Z_2 < Z_1$ from ergFET

$V_{\text{out}}$, (Volts)
ergFET Electrical Potential Measurements
of a Single Tribo-electrically Drawn Line on Polymer Sheet

0.333 cm/sec scan speed
Quasi-static power supply at +3V to +9V @ 3 Hz;
Ephemeral pump electrode at +9V
ergFET gate electrode is 3 cm from test object; compare to 3 mm for non-ergFET e-Sensor
Leakage effects are essentially removed and produce no shadowing as observed in the “N” in figure 12 for the non-ergFET e-Sensor
Electric Potential and Electric Field Imaging with Applications

2D EFI
Electric Potential and Electric Field Imaging with Applications
Demonstration Test Set Up

Object of interest is a circuit inside an optical flash strobe.

- Polymer container
- Sensor array cover
- Sensor array
Individual element sensor responses due to changes in strobe circuit electrical potentials

Measured voltage, $V$

Strobe electrical components are activated (charged)

Strobe starts discharging (flashes)

Strobe components charging

Sensor A

Sensor B

$0 \leq t \leq t_0 + \Delta t$

Time (seconds)
2D e-Sensor Electrical Potential Image of Activated Strobe Circuit in a Container

lightest shade represents a voltage drop of $\Delta V = -0.224$ volts
e-Sensor Linear Array Scan - Electrical Potential Image

~ 26 Hz AC waveforms observed

HV source on left side; RC circuit on right side (front surfaces 4” from e-Sensors) @ 12 VDC

Shaded region (low potential generated @12 VDC) is overlapping with objects’ locations

Ripples in image are due to low frequency AC
e-Sensor Linear Array Scan - Electrical Potential Image of Hidden Active Circuit

~ 26 Hz AC waveforms observed

HV source on left side; RC circuit on right side (front surfaces 4” from e-Sensors) @ 12 VDC

Electric Potential Image

Shaded region (low potential generated @12 VDC) is overlapping with objects’ locations

Ripples in image are due to low frequency AC
**e-Sensor Linear Array Scan - Electrical Potential Image**

~ 26 Hz AC waveforms observed

HV source on left side; RC circuit on right side (front surfaces 4” from e-Sensors) @ 12 VDC

Horizontal banding is due inadequate sensor-to-sensor calibration

AC signals from imaged sources

~ 36”

~ 9”
Electric Field Imaging of Plasmas
Electric Potential Image

Match Head > Location
2D Electric Field Imaging of Combustion

Electric Starting Lighter

August 15, 2016
Electric Potential Image of Ignited Lighter
Electric Field Imaging (EFI) of Ion Gun Plasma

August 16, 2016
Electric Potential and Electric Field Imaging with Applications

2D e-Sensor Array & Ion Gun
Electric Potential Image of Operating Ion Gun

Region of Lowest Potential

Plasma flow pattern
Phonon-Electric Field Imaging (EFI)

Real-time 2D EFI Array System
Phonon Assisted Dipole Creation
Optical Image of Object

Electrical potential of phonon generated dipoles

Linear grey scale
$\Delta V = 0.2$ Volts
3D Electric Field Imaging (EFI) & Electric Field Imaging Eye
Example configuration for 3D Electric Field Imaging

Sensor Array

Object of interest

\[ \Delta R_{\text{SCANNER}} \]

\[ \Delta Z_{\text{SCANNER}} \]

\[ \alpha \]

\[ \varphi \]

\[ \phi \]

\[ \beta \]

\[ \omega \]

\[ \Delta R_{\text{OBJECT}} \]

\[ \Delta Z_{\text{OBJECT}} \]

\[ \theta_{\text{OBJECT}} \]

Scanner Base

Scanner Base Axis

\[ \Psi \]
Electric Field Imaging Eye
Anticipated Benefits

**NASA Programs and Commercial space industry**
- Electrostatic discharge (ESD) mitigation and control requirements
- Damaged materials characterization requirements
- Component operations and integrity
- Remote active circuit characterization
- Tether and insulation quality control
- Lightening Prediction
- Vehicle and component charging requirements
- Design and construction of unique electronic sensors
- Systems and human health monitoring in space
- Astronaut EVA safety

**The Nation**
- Intrusion detection
- US perimeter security
- Transportation security - personnel and baggage inspection
- Personnel identification and access
- Electronic signature requirements
- National power grid integrity
- Crime scene forensics
- Molecular memory
- Medical – non-contact EKG and EMG (electromyography)
Electric Potential and Electric Field Imaging with Applications

Q & A

Patent Activities

- Electric Field Imaging (2016)  US 9279719 B2
- Quasi-Static Electric Field Generator (2016)  US20160049885A1
- Solid State Ephemeral Electric Potential and Electric Field Sensor, Serial Number: 15/177,798 (2016)
For EFI technology listing and licensing opportunities:

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https://technology.nasa.gov/patent/LAR-TOPS-116

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