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).**
e-Sensor Array Based on Field Effect Transistors

Resistance load

Each gate (G) is a measurement electrode

To data acquisition system
Electric Potential and Electric Field Imaging with Applications

Floating gate design
Dielectric constant, relative permittivity, $\varepsilon$

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

$\varepsilon = 1$ vacuum
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POSITIVE charge

NEGATIVE charge

Triboelectric affinity

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
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

Data Acquisition, Rotation, and Wireless Dipole Voltage Control Systems
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)
Electric Potential Image of Human


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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\[ E(x_i, y_i, z_i) = -\left( \frac{V(x_{i+1}, y_i, z_i) - V(x_i, y_i, z_i)}{x_{i+1} - x_i} \right) \hat{i} + \left( \frac{V(x_i, y_{i+1}, z_i) - V(x_i, y_i, z_i)}{y_{i+1} - y_i} \right) \hat{j} + \left( \frac{V(x_i, y_i, z_{i+1}) - V(x_i, y_i, z_i)}{z_{i+1} - z_i} \right) \hat{k} \]
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
Electric Potential and Electric Field Imaging with Applications

Electric Potential Image
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>
<tr>
<td></td>
<td></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

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

Residual Charge Due to Charge Buildup at $\tau_1 = \tau + \Delta \tau > 0.0$
e-Sensor data write test bed system – identifying organic memory parameters

**Figure 7**

- **a**: Diagram showing the layout of the test bed system, highlighting various components such as electrode supports, array support, potential control resistors, conducting strips, data storage panel, and hinges.
- **b**: Close-up of the electrode supports and array supports.
- **c**: Detailed view of the data storage panel and electrode wires.
- **d**: Perspective view of the adjustable height electrode supports.

**Legend:**
- **Electrode**: Conducting strips and electrodes are used for data acquisition.
- **Array support**: The structure holding the array of electrodes.
- **Potential control resistors**: Used to adjust the electrical potential.
- **Conducting strips**: Wire connections between components.
- **Data storage panel**: Platform for data collection.
- **Hinges**: Mechanisms for adjusting the height.

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
Back side of data storage panel
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Foot Prints on Static Protection Office Rug

Footfalls are outlined in dashed curves

Optical Image of Rug Surface

EFI Image (electrical potential)

Optical Image of Bottom of Right Shoe

1.219 m
27.94 cm

ΔV = - 4.46 Volts

5 minutes
Electric Potential and Electric Field Imaging with Applications

Very conservative sensitivity at 1.55mV/cm

Several orders of magnitude by FET selection, components, filtering, structural design, etc.
Ephemeral e-Sensor
Electric Potential and Electric Field Imaging with Applications

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

Time, Seconds
Typical Measured Ephemeral Sensor Response in the Presence of a Charged Axially Symmetric Object

Non-rotating sensor

Rotating sensor
Solid State
Ephemeral e-Sensor
Solid State Ephemeral Sensor, ergFET

Equilibrium Pump

Drain
Source
Gate
n-Channel JFET Based ergFET

with Equilibrium Pump and Quasi-static Direct Potential Controls

[Diagram of n-Channel JFET with labels: ergFET, Drain, Gate, Source, V_g, V_s, V_d, V_p, V_EPC, S_1, S_2, S_3, S_4, V_{QSDP}, V_o, V_{o(\tau)}, V_s, V_{s(\tau)} and additional controls like V_{p, feedback}, equilibrium pump control, and feedback equilibrium pump control.]
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

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

Time

V_{out}

0

Trigger

Electrostatic Potential

Position on X-Axis

Equilibrium Potential

Non-ergFET Sensor

Leakage Effect

ergFET Yields Symmetric Electrostatic Potential and Image Representation
V_{pump}, Equilibrium Pump Voltage (Volts)

![Graphs showing voltage changes](image)

- **No Charged Object**
- **Charged Object at a Distance Z_1 from ergFET**
- **Charged Object at a Distance Z_2 < Z_1 from ergFET**
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

Ephemeral ergFET Potential, (Volts)

Equilibrium Potential

Time (seconds) 0 764.45
Electric Potential and Electric Field Imaging with Applications

2D EFI

[Diagram of electrical circuitry]

[Image of equipment setup]

[NASA Ed Generazio e-Sensor calibration controller 12/29/2014]

[Poster: "Sensor Unleashed: The Movie"]
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
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

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
Electric Field Imaging of Plasmas
Ranges of Plasmas

- Centre of Sun
- Metals
- Lasers
- Photosphere
- Fusion
- Chromosphere
- Solar corona
- Magnetosphere
- Interplanetary
- Solar wind
- Interstellar
- Galactic

Electron Density (e^-/cm^3)

Temperature (eV/K)
Electric Potential Image

Match Head > Location
2D Electric Field Imaging of Combustion Electric Starting Lighter

August 15, 2016
Electric Potential Image of Ignited Lighter

Extinguishing rings
Electric Field Imaging (EFI) of Ion Gun Plasma

August 16, 2016
2D e-Sensor Array & Ion Gun
Electric Potential Image of Operating Ion Gun
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

$\Delta Z_{\text{scanner}}$

$\phi$

$\beta$

$\phi_{\text{object}}$

$\Delta R_{\text{scanner}}$

$\Delta R_{\text{object}}$

$\Delta Z_{\text{object}}$

$\omega$

$\alpha$

$\theta_{\text{object}}$

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)
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:

Jesse Midgett, Technology Transfer Specialist

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

LARC-DL-technologygateway@mail.nasa.gov