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

FET

Each gate (G) is a measurement electrode

To data acquisition system

V1

V2
Electric Potential and Electric Field Imaging with Applications

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

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

$\varepsilon = 1$ vacuum

Conductor
Electric Potential and Electric Field Imaging with Applications

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
Electric Potential and Electric Field Imaging with Applications

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

Electrical equipotential surfaces (V₁, V₂, V₃, V₄) 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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2\textsuperscript{nd} Prototype
Electric Potential and Electric Field Imaging with Applications

Maximum (black) = 0.97 v/cm
Minimum (white) = -0.58 v/cm

X-Component of Electric Field

Image Processing

Conducting Equipotential Surface, $V_{\text{surface}}$

Uniform Electric Field, (infinite plate approximation)

Quasi-Static e-Field Generator

Equipotential Contours, $V_n$

Triboelectrically Neutral Casing

Dipole Element

Electric Field Lines (lines of force)

Electrical Insulator

Object Being Inspected

Data Acquisition, Rotation, and Wireless Dipole Voltage Control Systems

e-Sensor Array

Conveyor

Y

Z
Voltage Response from 16 e-Sensors

Dipole Rotation Rate = 120 RPM
Quasi-static Electric Field Frequency = 2 Hz
Electric Potential Image of Human


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
Electric Potential and Electric Field Imaging with Applications

![Image of front and back views with dimensions 15.24 cm]

- **a.** Front and back views

- **b.** Electric Potential
- **c.** Electric Potential 3D
- **d.** Electric Potential 3D 45°
\[ E(x_i, y_i, z_i) \approx -\left( \frac{V(x_{i+1}, y_i, z_i) - V(x_i, y_i, z_i)}{x_{i+1} - x_i} \right) \hat{i} + \left( \frac{V(x_i, y_{i+1}, z_i) - V(x_i, y_i, z_i)}{y_{i+1} - y_i} \right) \hat{j} + \left( \frac{V(x_i, y_i, z_{i+1}) - V(x_i, y_i, z_i)}{z_{i+1} - z_i} \right) \hat{k} \]
Electric Potential and Electric Field Imaging with Applications

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).

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).

Representation of Cable Showing
Cable Orientation RG-174/U 50 OHM
Cable 0.256 cm Outer Jacket Diameter

100 cm

200 mm

LM324 DIP OP AMP Location
19

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></td>
<td>Copper</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

Suspect object in container

Electrode

Applied Electric Field

Electrode

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

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

Initial Polarization Due to Bound and Unbound Charges at $\tau = 0.0$
e-Sensor data write test bed system – identifying organic memory parameters

Figure 7

a) Array support
b) Electrode supports
Array support
Adjustable Height Electrode supports
Electrode wires
Electrode

Array support
Hinges
Array support
Mountain Bracket
Electrode
Adjustable Height Electrode supports
Data Storage Panel
Storage Panel
Electrode
Data Storage Panel
After Erasure

McMaster Label on back side reveals new inspection technology for hidden objects.

Data writes without using a triboelectric process

EFI image of Electrical Potential of Data Stored by Charge Distribution on PTFE

Electric Potential Images
Back side of data storage panel
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

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

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
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

Time, Seconds
Equilibrium electrical potential

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

Non-rotating sensor

Rotating sensor

X-Axis

Position on X-Axis

Electrical Potential (-V)

Equilibrium electrical potential

Position on X-Axis

Electric Potential and Electric Field Imaging with Applications
Solid State
Ephemeral e-Sensor
Solid State Ephemeral Sensor, ergFET

Equilibrium Pump
n-Channel JFET Based ergFET
with Equilibrium Pump and Quasi-static Direct Potential Controls
Cylindrically Symmetric Charged Object

erfFET Sensor

Non-erfFET Sensor

Z-axis

$Z_1$

$Z_2$
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

ergFET Sensor
- Electrostatic Potential
- Equilibrium Potential

Position on X-Axis

ergFET Yields Symmetric Electrostatic Potential and Image Representation
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
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
- Strobe components discharged
- Time (seconds) $\tau_0$, $\tau_0 + \Delta \tau$

Electric Potential and Electric Field Imaging with Applications
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

$\tau_0$

$\tau_0 + 0.06$ sec
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
RANGES OF PLASMAS

Electron density (electrons per cubic centimetre) vs. temperature (eV K)

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

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

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

$\Delta Z_{\text{SCANNER}}$

$\Delta R_{\text{SCANNER}}$

$\Delta R_{\text{OBJECT}}$

$\Delta Z_{\text{OBJECT}}$

$\phi$

$\phi_{\text{OBJECT}}$

$\beta$

$\omega$

$\alpha$

$\theta_{\text{OBJECT}}$

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)
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

LARC-DL-technologygateway@mail.nasa.gov