Exceptional service in the national interest

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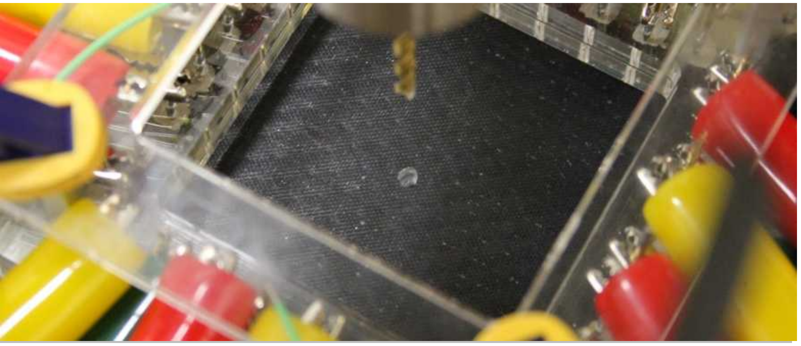

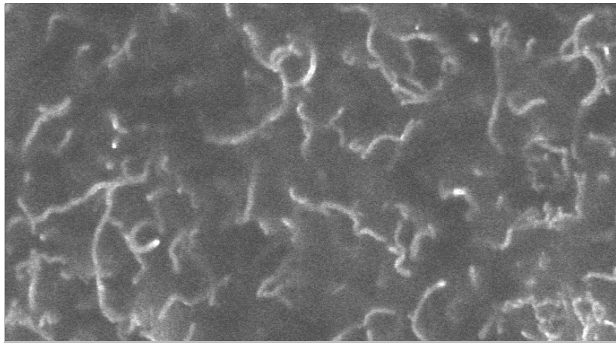

Electrical Impedance Tomography Data Acquisition Unit

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[1]Sandia National Laboratories, Livermore, CA, USA

U.S. DEPARTMENT OF ENERGY

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NNSA National Nuclear Security Administration

Usage of Fiber-Reinforced Composites

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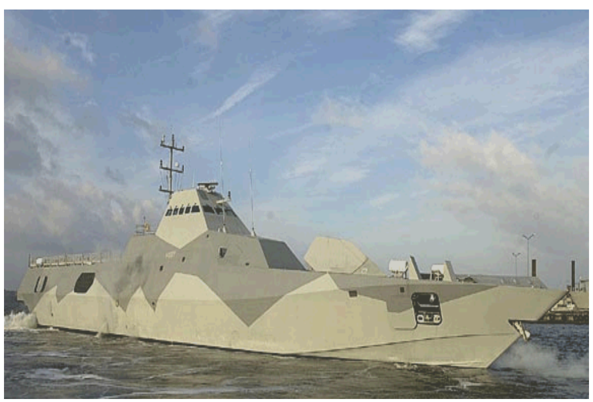
- Over the past 50 years, increased usage of composite materials

Commercial aircraft systems

Future and legacy spacecraft

Military aircraft



Naval structures

Wind turbine blades

CFRP cable stay bridge

Composite Damage Modes

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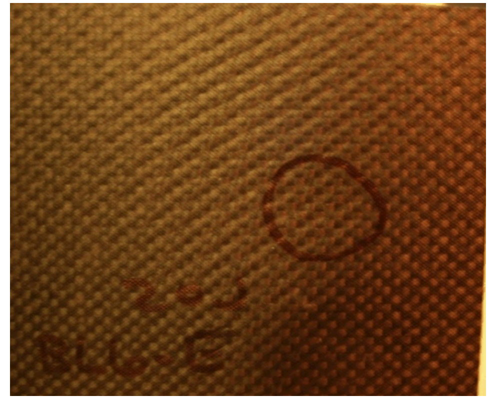
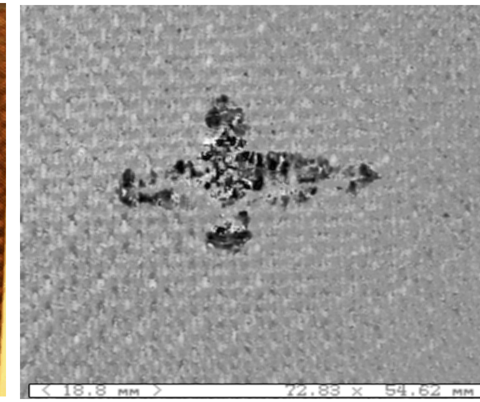
- Susceptible to damage due to:
  - Strain, impact, chemical penetrants, multi-axial fatigue
- Damage modes:
  - Matrix cracking
  - Fiber-breakage
  - Delamination
  - Transverse cracking
  - Fiber-matrix debonding
  - Matrix degradation
  - Blistering
- Difficult to detect
  - Internal to laminate structure
  - Nearly invisible to naked eye
  - Current methods are laborious



Visual inspection



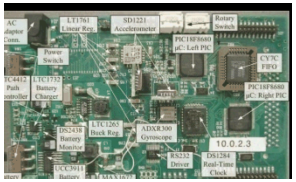
C-SCAN ultrasound image

CFRP panel after 20 Joule impact

Aircraft ultrasonic inspection (Composites World)

Emerging Sensing Technologies

Wireless Sensors and Sensor Networks

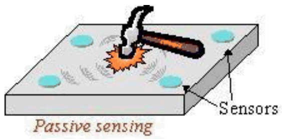



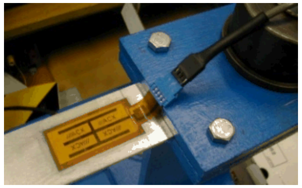
WiMMS
Wang, *et al.* (2008)

UCI DuraNode
Chung, *et al.* (2005)

- **Advantages:**
  - Low cost
  - Dense instrumentation
  - Reconfigurable
- **Disadvantages:**
  - Point sensors
  - Indirect damage detection
  - Physics-based models

Ultrasonics and Guided-Waves

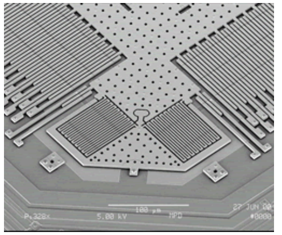
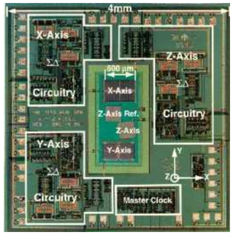




Array of piezoelectric ceramic sensors and actuators

- **Advantages:**
  - Sensors and actuators
  - Spatial damage detection
- **Disadvantages:**
  - Indirect damage detection
  - Wave propagation models or pattern recognition
  - Thin structures
  - Expensive data acquisition

Micro-electromechanical Systems (MEMS)

AD *i*MEMS
Weinberg (1999)

3-axis accelerometer
Lemkin (1997)

- **Advantages:**
  - Miniaturized sensor designs
  - Complex sensors/actuators
- **Disadvantages:**
  - "Top-down" design
  - Expensive fabrication equipment
  - High costs
  - Sensor sensitivity on par with macro-scale counterpart

SHM Design Considerations

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Current SHM limitations:

- Indirect sensing approaches
- Point-based sensing
- Tethered sensors
- Lack of system scalability

Boeing 787 (Boeing)

Successful SHM systems:

1. Directly detect and measure damage
2. Determine the damage location
3. Ascertain the size of the damage
4. Quantify the severity of the damage
5. Achieve multi-modal sensing capabilities (i.e., delamination, cracking, and chemical penetration)

Golden Gate Bridge (Wikipedia)

Spatially Distributed SHM Paradigm

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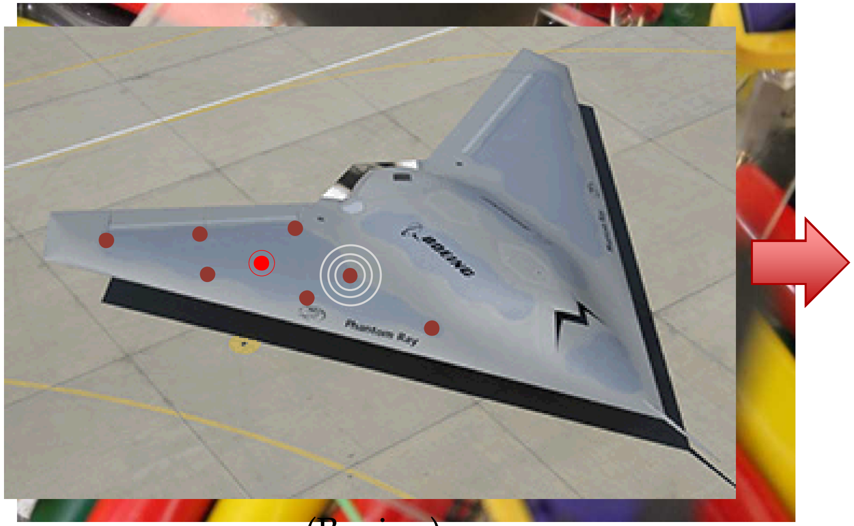
- Current state-of-art in structural health monitoring:
  - Passive SHM using acoustic emissions
  - Active SHM using piezoelectric sensor/actuator pairs
- "Sensing skins" for spatial damage detection:
  - Objective is to identify the location and severity of damage
  - Monitor and detect damage over two- (or even three) dimensions
  - Direct damage detection

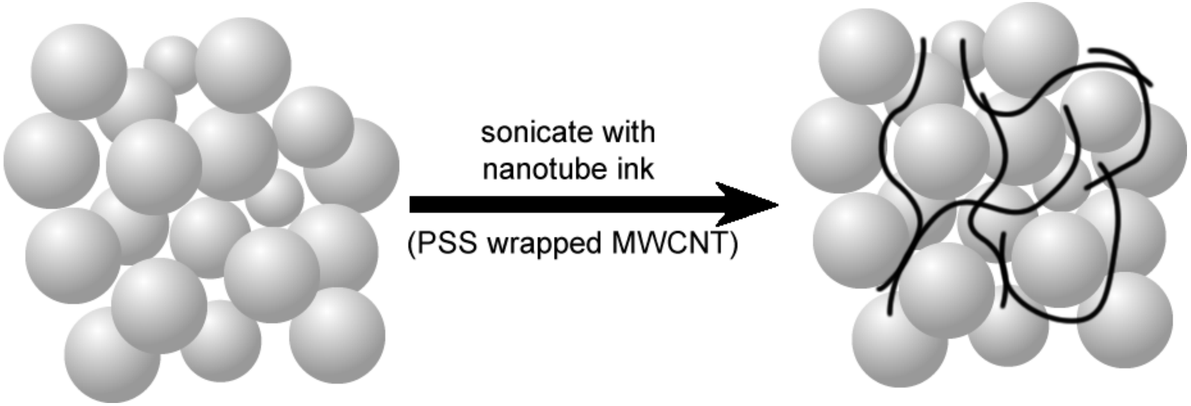


(Boeing)

(Boeing)

Sprayable MWNT-Latex Thin Film

- Rapid large-scale deposition
  - Required for mass deployment of methodology
- MWNT-PSS/Latex paint formulation
  - Collaborated to improve initial Sandia formulation
  - Sub-micron PVDF creates mold for MWNT organization
  - Off-the-shelf deposition method

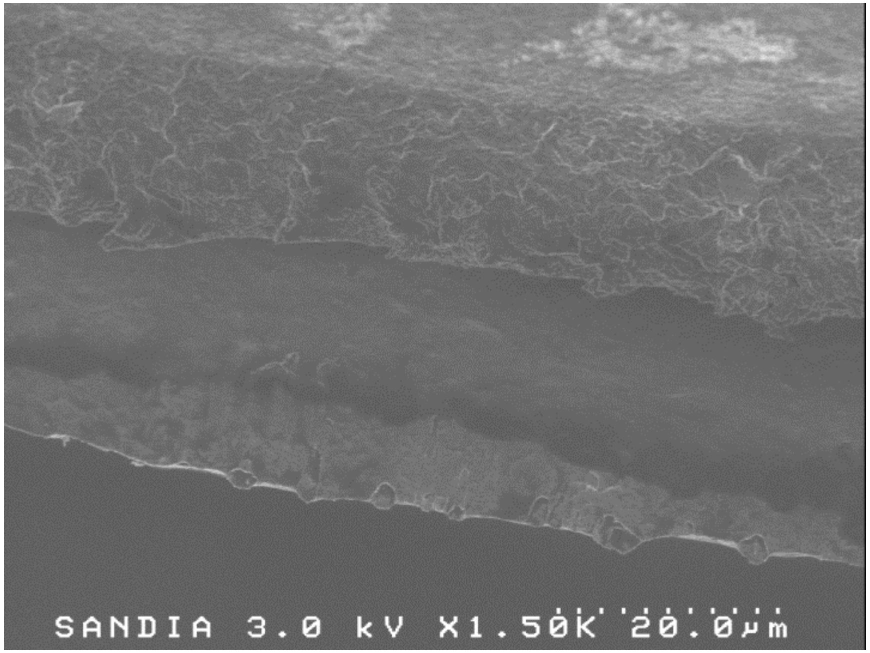


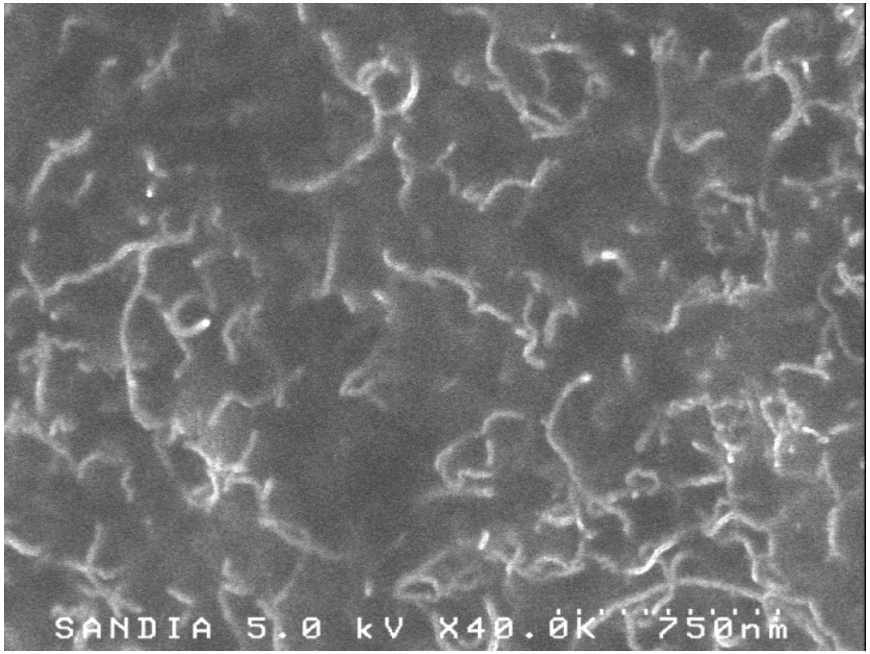
Kynar Aquatec™ latex solution (avg. particle size 150nm)

Forms segregated MWCNT network

MWNT-Latex Morphology

- Creation of MWNT networks:
  - Electrical percolation above 1 wt% MWNTs
- Fiber-reinforced polymer deployment:
  - Surface applied to post-cured composites
  - Applied to fiber weaves for embedded sensing



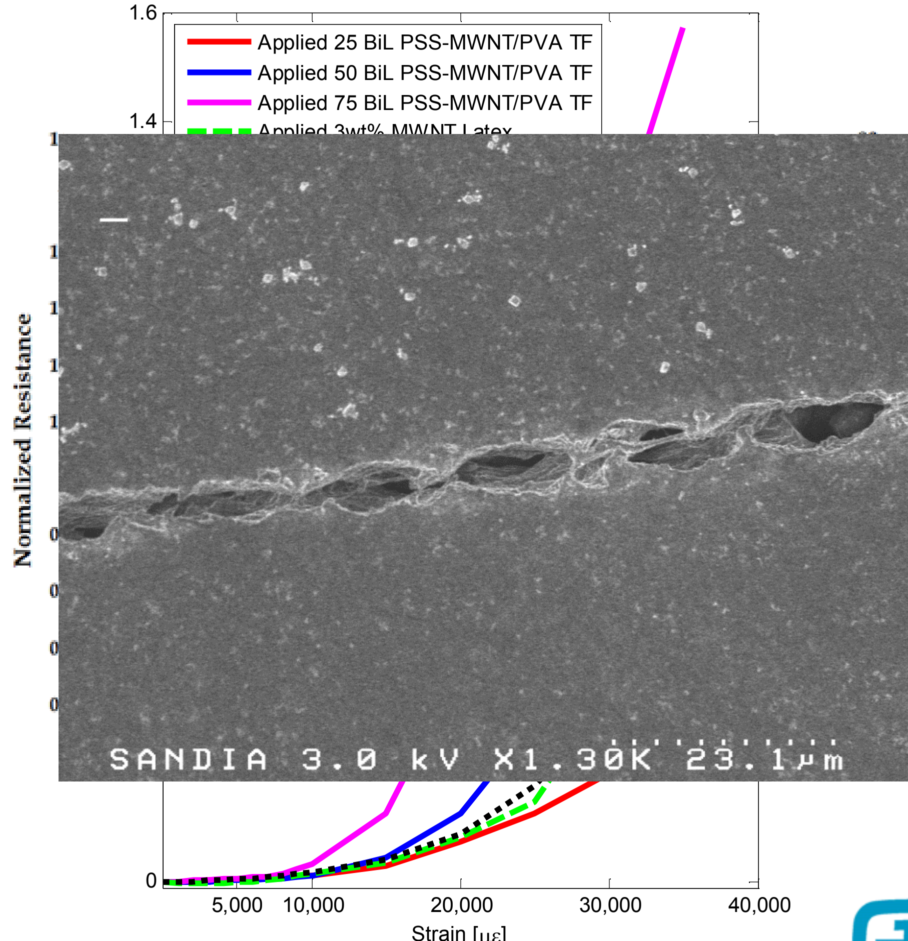


Cross-section and MWNT network SEM images of 3wt% MWNT-Latex film

MWNT-Latex Characterization

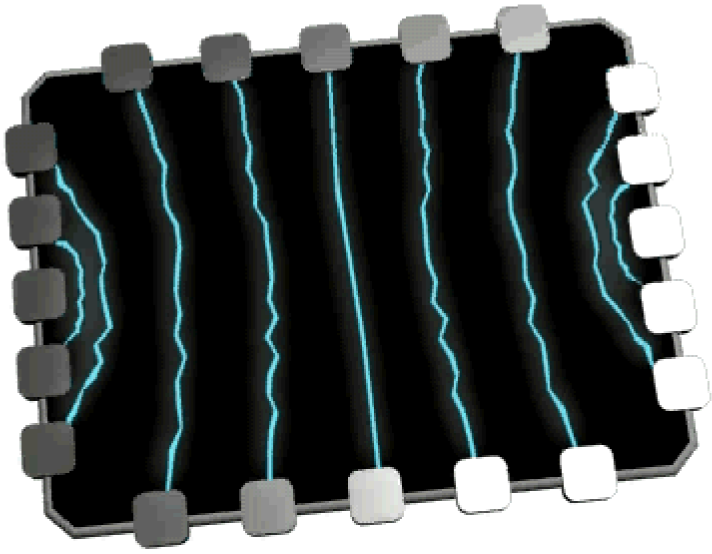
- Electromechanical characteristics:
  - Quasi-static testing
    - Nearly same sensitivity as LbL
  - Bi-functional strain response
    - Linear
    - Quadratic
      - Cracking of film

- Thermo-resistance coupling:
  - -50°C to 80°C over 2 hours
  - 2 hour holds
  - Inversely linear relationship
  - Non-linear response @ -30°C
    - ~ T_g of PVDF
    - Restructuring of MWNTs



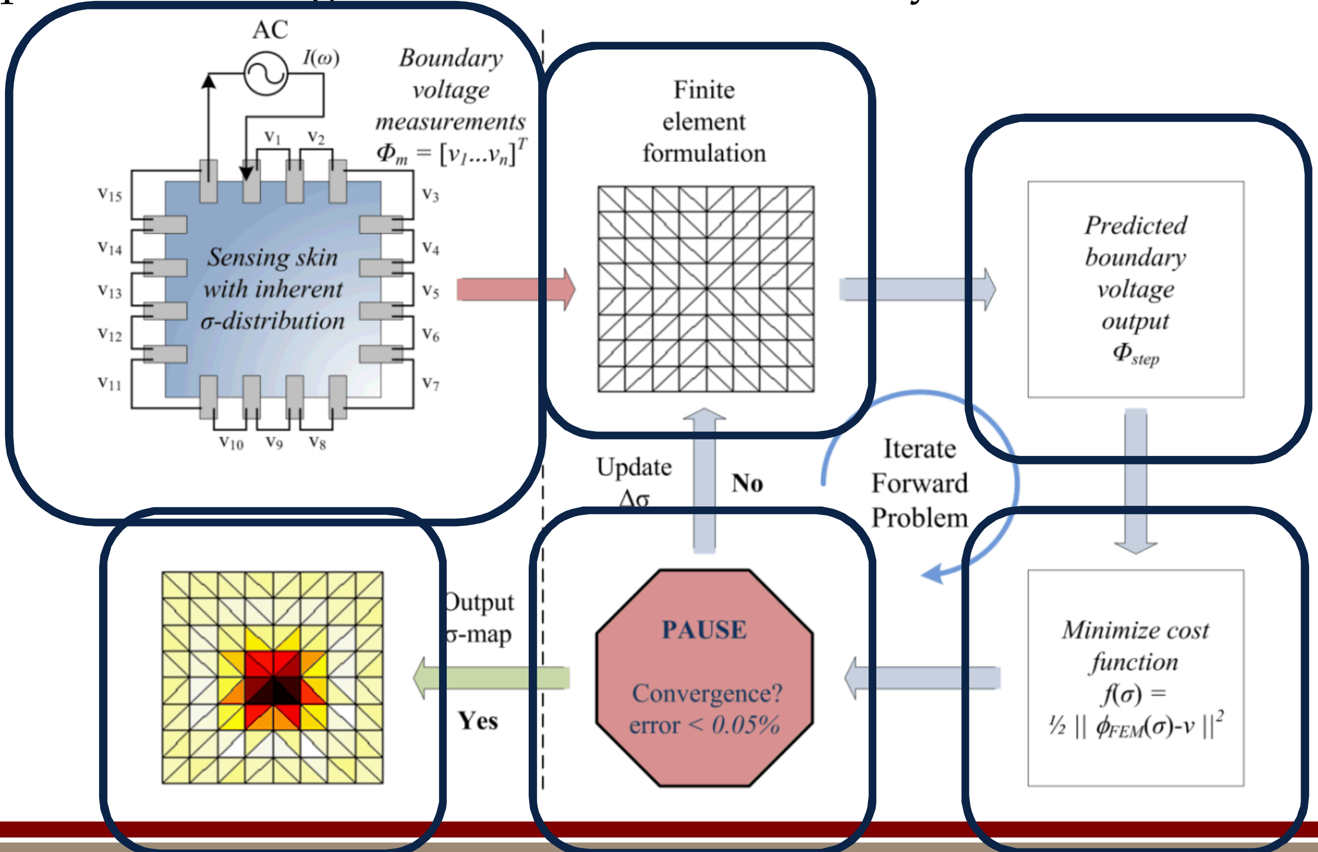
Electrical Impedance Tomography

- Overview of spatial conductivity mapping
  - Since film impedance calibrated to strain, conductivity maps can correspond to 2-D strain distribution maps



Typical EIT Reconstruction

- Laplace's equation:
  - $\nabla \cdot (\sigma \nabla \phi) = 0$, where σ can vary by orders of magnitude
  - Governs potential and conductivity relationship
- Forward problem: conductivity known, solve voltage
- Inverse problem: voltage known, solve conductivity



Linear EIT Reconstruction

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- Reconstructs small σ changes:
  - Typically difference imaging
    - $\sigma_1 - \sigma_2 << \sigma_2$
- Maximum a posteriori (MAP):
  - H: sensitivity matrix

$$H(\sigma_{bkgd})_{ij} = \frac{\partial V_i}{\partial \sigma_j}$$

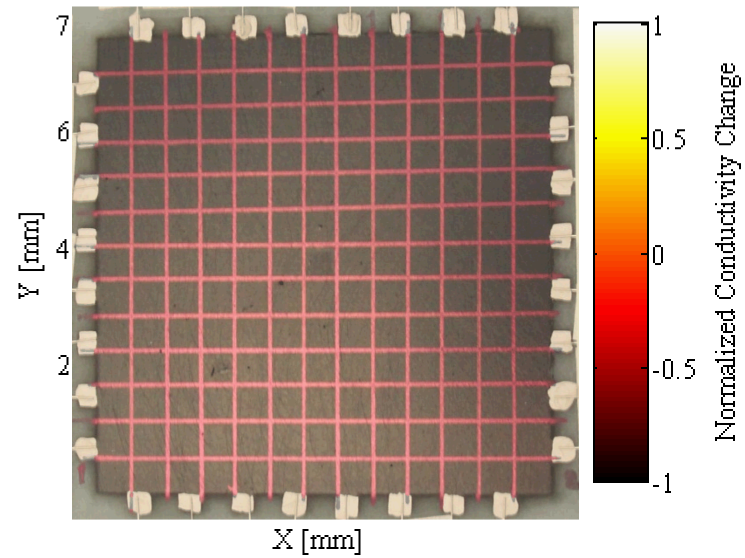
  - Regularization hyperparameter: λ
    - Noise figure

$$NF(\lambda) = \frac{SNR_{in}}{SNR_{out}} \approx 1$$

    - Use representative σ distribution
  - W: Noise model
  - R: Regularization matrix
- Advantages:
  - Can pre-calculate H
  - Many damage modes lead to small changes in σ

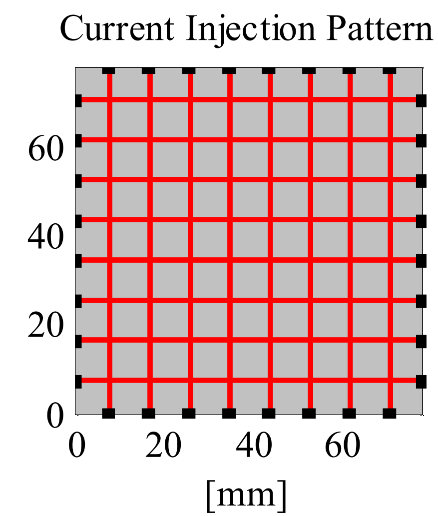
$$\frac{\Delta\sigma}{\sigma_0} = \left(\underline{H}^T W \underline{H} + \underline{\lambda} R\right)^{-1} \left(\underline{H}^T W\right) \frac{\Delta V}{V_0}$$

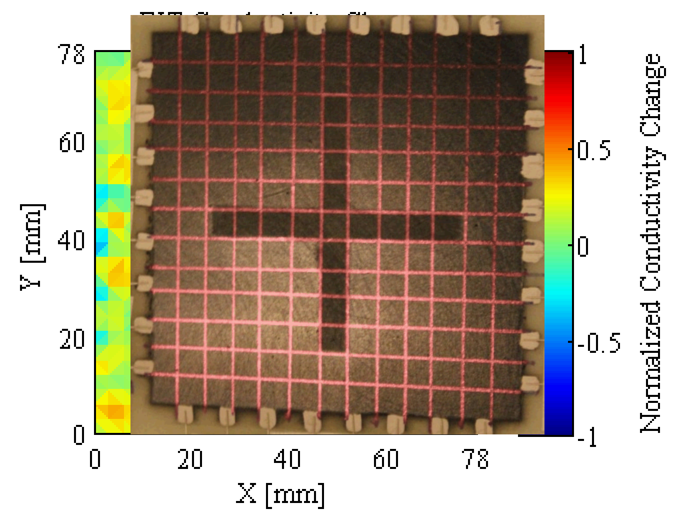
$$\frac{\Delta\sigma}{\sigma_0} = B\Delta \frac{\Delta V}{V_0}$$



Validation EIT

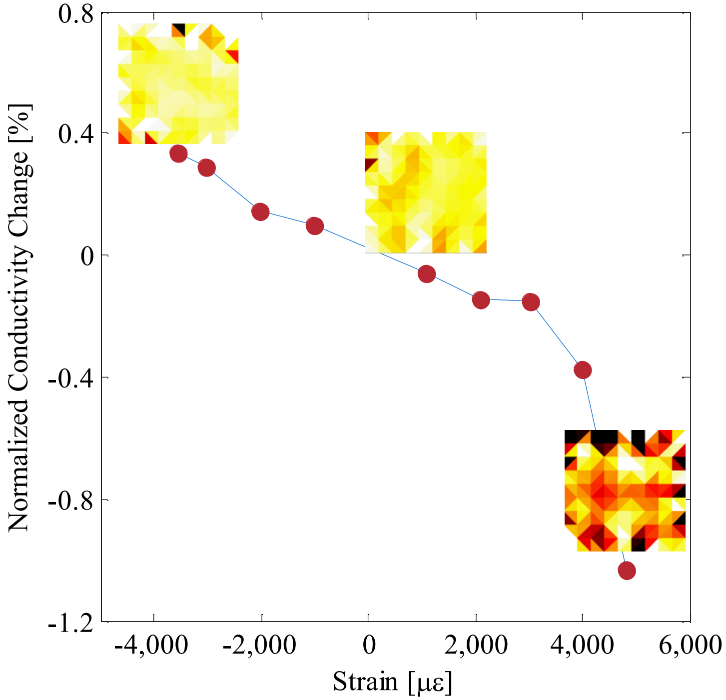
- Applied sensing measurements
  - MWNT-Latex deposited upon cured GFRP composites
  - 78 mm x 78 mm sensing region
  - 8x8 electrodes scheme = 32 electrodes
    - 3 mm electrodes
    - 6 mm spacing
- Investigate stability and efficiency:
  - Computational demand
    - ~ 1 s reconstruction time
- Accuracy characterization:
  - Conductivity:
    - Point-to-point resistance map via 4-pt probe
  - Spatial feature ID sensing resolution
    - ~ 6 mm cross at center with -50% Δσ

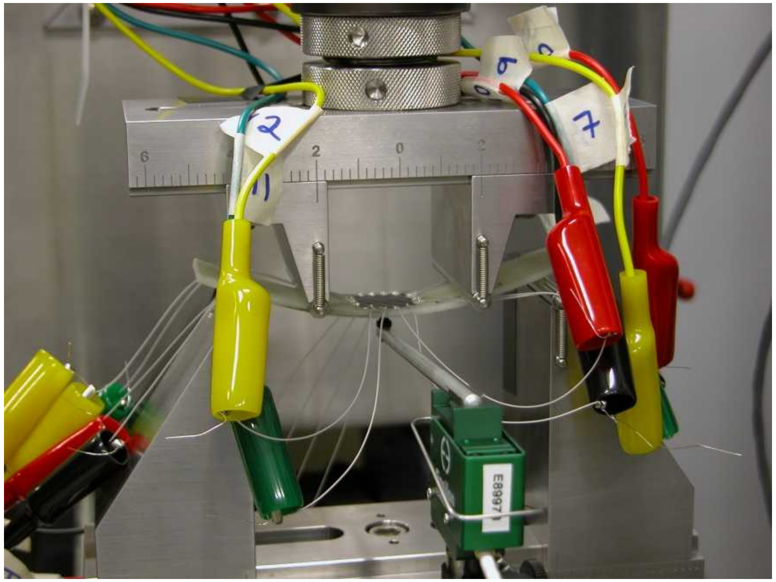




Spatial Strain Sensing

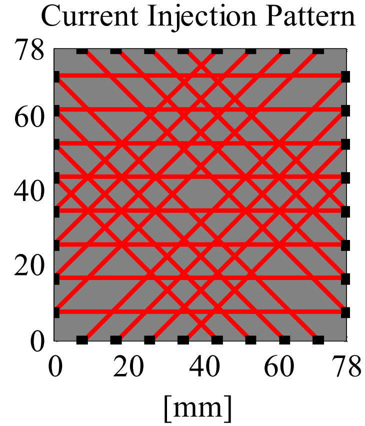
- 4-pt bending
  - **ASTM D7264**
  - MWNT-Latex on GFRP
  - Stepped displacement profile
  - Tensile/compressive strain
- Strain sensitivity
  - Nearly linear

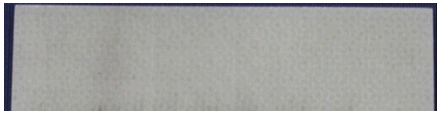


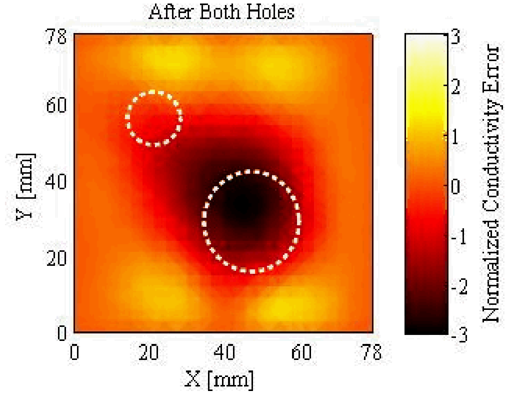


Embedded Spatial Sensing

- Embedded sensing architecture
  - MWNT-Latex on GF fiber weave
  - Embedded within epoxy matrix
- Specimens
  - $[0°/+45°/90°/-45°]_{2s}$
  - Unidirectional GF
  - 150 mm x 100 mm
    - ASTM D7146 Standard
- Anisotropic EIT
  - Isotropic ► Anisotropic
  - Scalar ► Matrix: σ
  - $\sigma_{0°} > \sigma_{90°}$ by ~2:1
  - $\nabla \cdot (\sigma \nabla \phi) = 0$

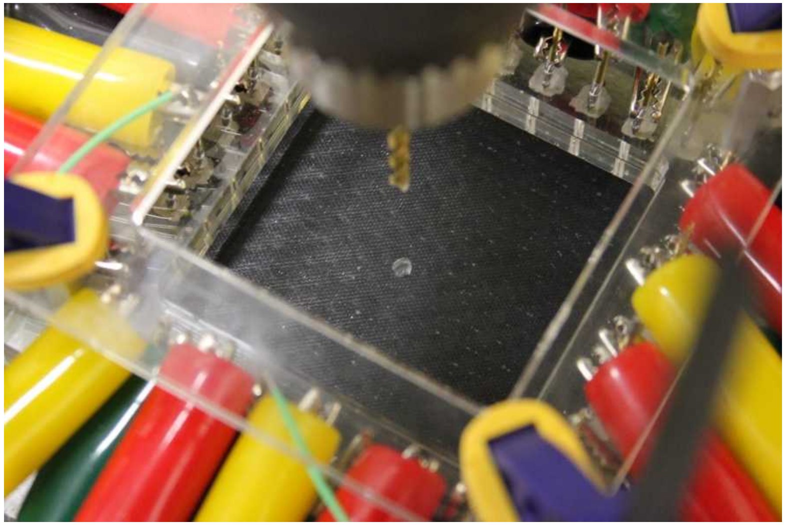


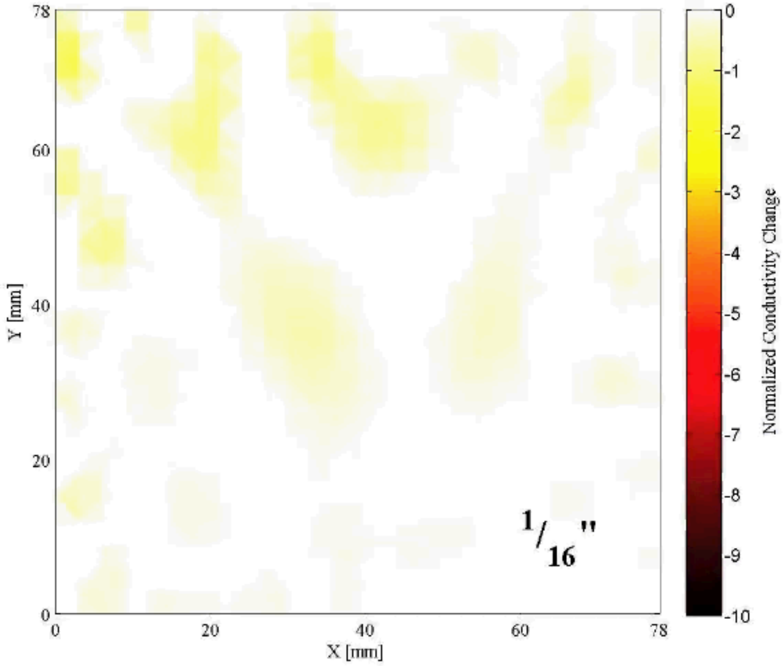




Embedded Spatial Sensitivity

- Embedded sensing validation:
  - Determine conductivity change sensitivity
  - Process:
    - Progressively larger drilled holes:
    - $^1/_{16}''$, $^1/_8''$, $^3/_{16}''$, $^1/_4''$, $^5/_{16}''$, $^3/_8''$, $^1/_2''$
  - Anisotropic EIT performed
    - Conductivity change from pristine sample

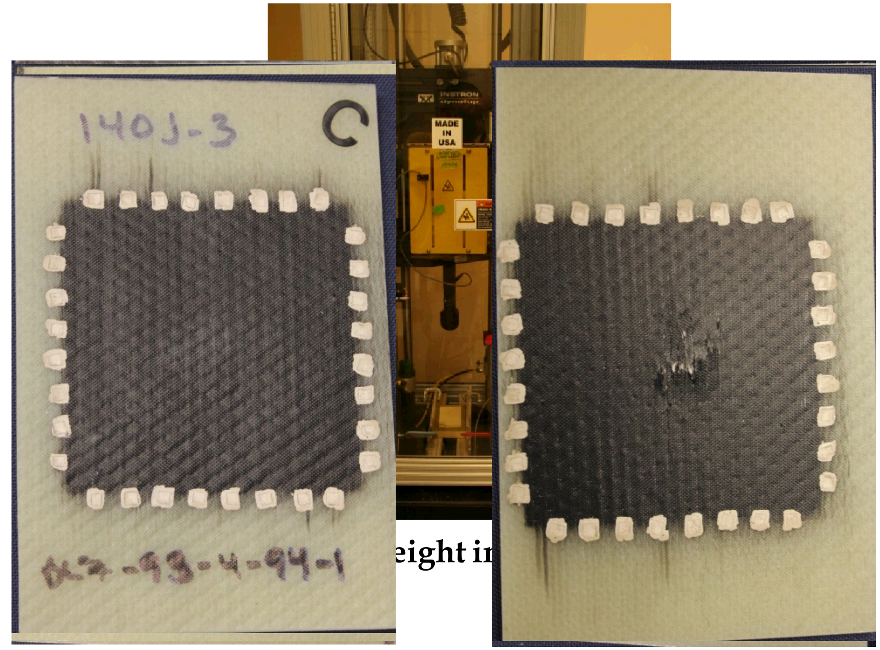


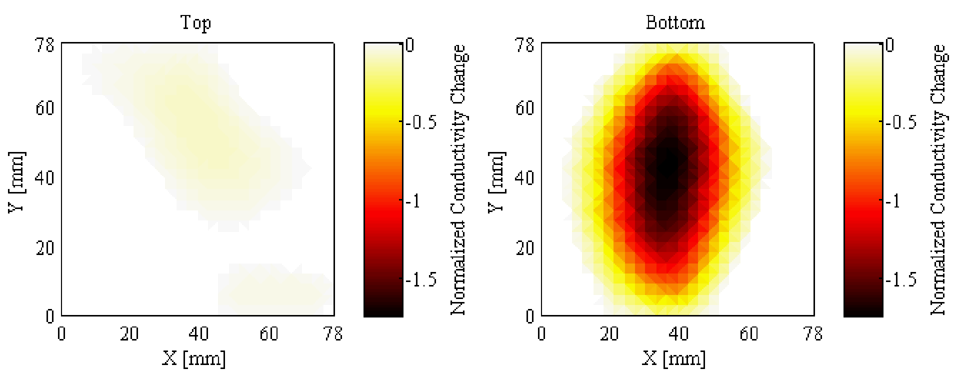


Impact Damage Detection

- Drop-weight impact tests
  - **ASTM D7146**
  - 78 mm by 78 mm sensing region
  - MWNT-latex on glass fiber weave
  - Impact energy: 20, 60, 100, 140 J
  - Before/after EIT measurements

- Verification:
  - Thermography
    - Matrix Cracking
    - Delamination
  - Photographic Imaging
    - Surface damage





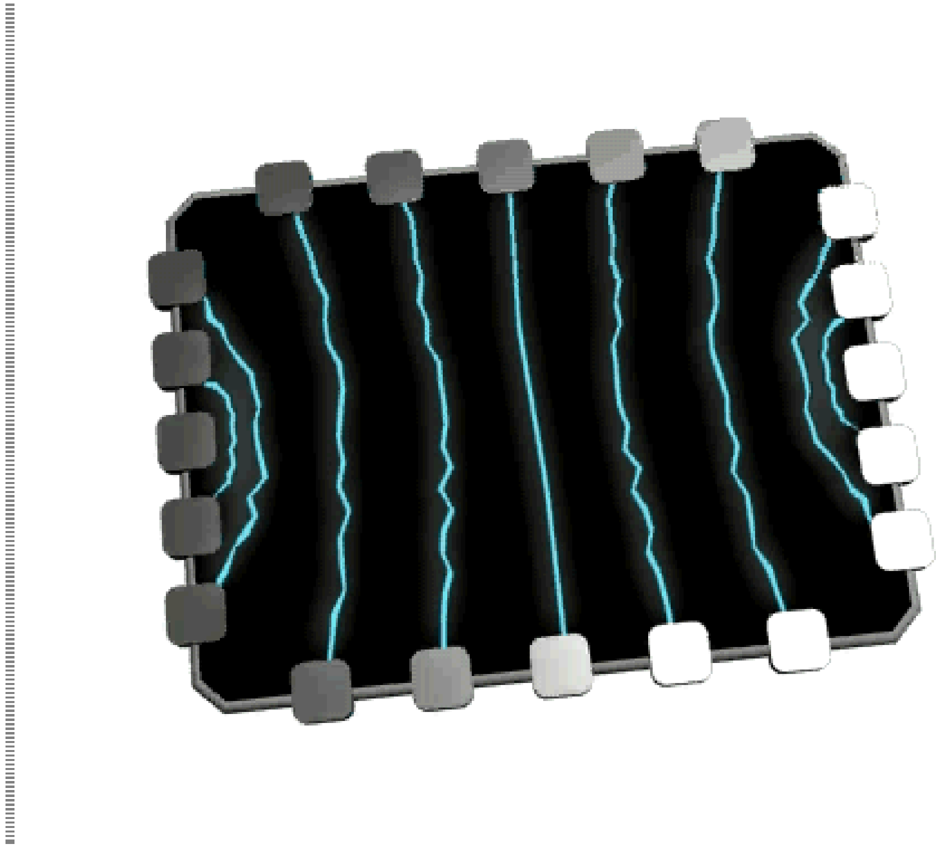
Project Details

- What are you being asked to do?
  - Design and fabricate a data acquisition that is capable of taking high-rate EIT measure
  - At present DAQ approach
    - Series measurements
    - Matrix switch used to route current and voltage measurements
    - Really slow…. About 90 s for each measurements previously discussed
  - Next generation DAQ unit
    - Parallel approach
    - Each electrode node has current source, analog-digital converter, and ground
    - Desire 100 Hz EIT sample rate
      - ~960 measurements in 0.01 s
      - ~10 kHz individual sample frequency
    - This sampling rate would allow for a real time monitoring of low-velocity impact events

Measurement Scheme

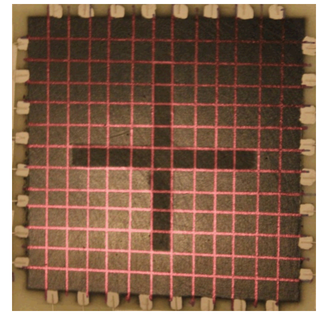
1. Inputs
   - Current parameters
2. Input parser
   - How measurement should be taken
3. Measurement
   - Parallel measurement scheme
4. Data management
   - How microprocessor handles the data from measurement
5. Saving data
   - Data saving format and file structure
6. Reconstruction
   - How/when reconstruction will be taken

How A Measurement Works…

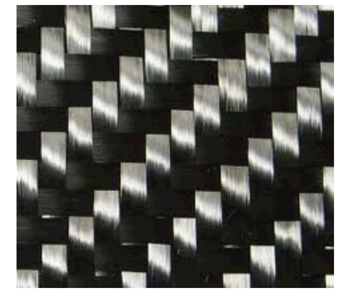


Inputs

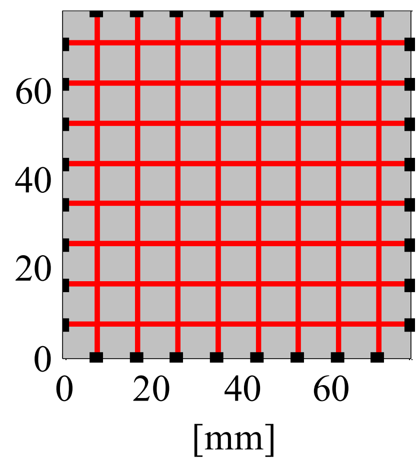
- Current magnitude
  - Will depend on SNR of voltage measurements
  - 1 µA to 100 mA
  - What's possible with chip-based current regulators?
- Current Injection Pattern
  - Which electrodes does current flow between?
  - Material dependent
  - Isotropic conductivity
  - Anisotropic conductivity

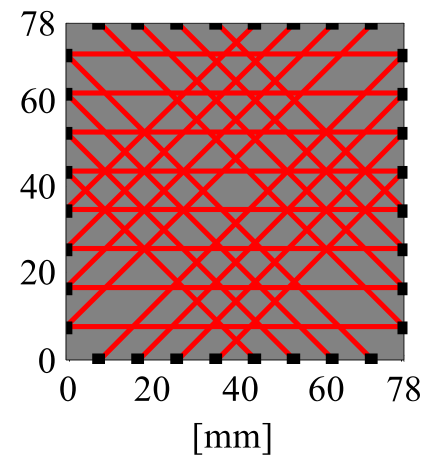


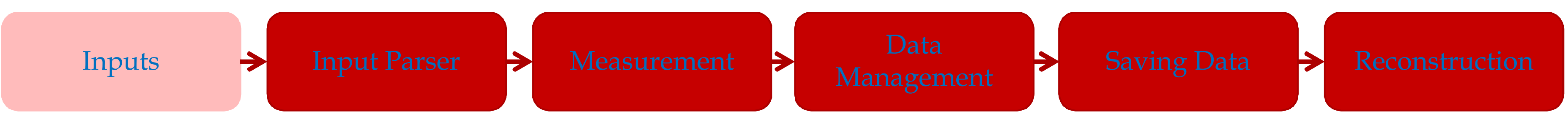
Isotropic Conductivity



Anisotropic Conductivity

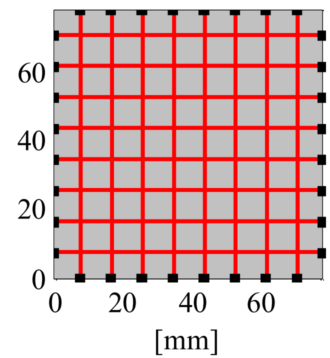






Input Parser

- From inputs, determine how measurement is made
  - Each current injection
    - Current injection electrode
    - Ground electrode
    - Voltage measurement electrodes
  - Setup triggering for each current injection/voltage measurement configuration
    - Current injected between two electrodes, wait some amount of time, take all voltage measurements at the same time

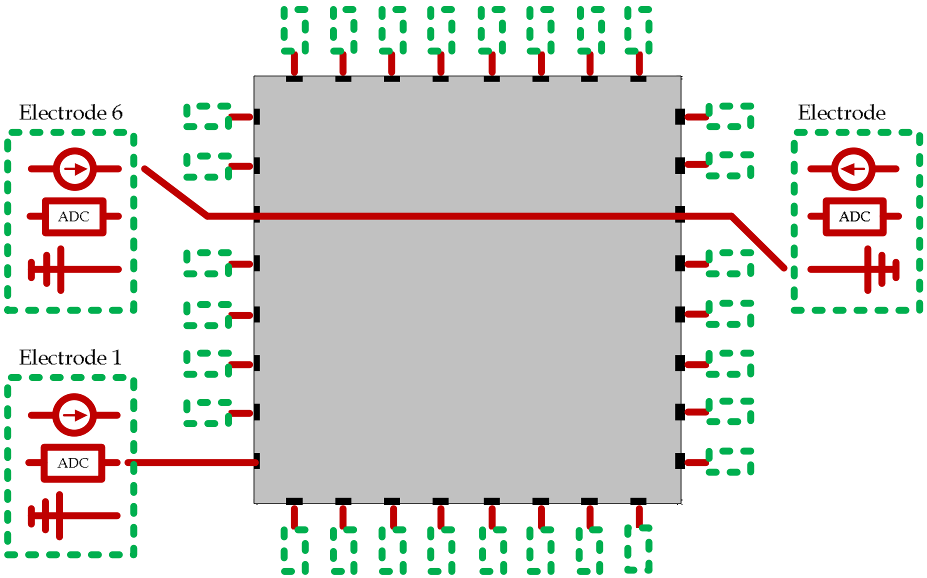


Measurement Methodology

Inputs → Input Parser → Measurement → Data Management → Saving Data → Reconstruction

Measurement

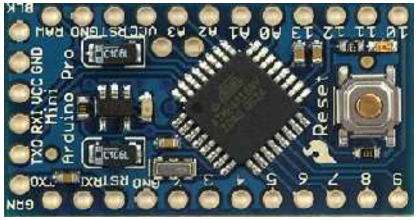
- Parallel Measurements
  - Current Source
    - Inject specified current
    - Measure actual current injected
  - Analog-Digital Converter
    - Voltage between electrode and common ground
  - Ground
    - Common ground
  - All occurring simultaneously

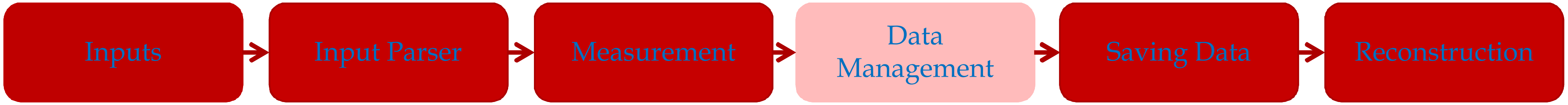


Inputs → Input Parser → Measurement → Data Management → Saving Data → Reconstruction

- How microprocessor handles data coming from ADCs
  - Data @ 100 Hz
    - 30 voltage measurements
    - 2 current measurements
  - Can designed architecture handle faster than this?

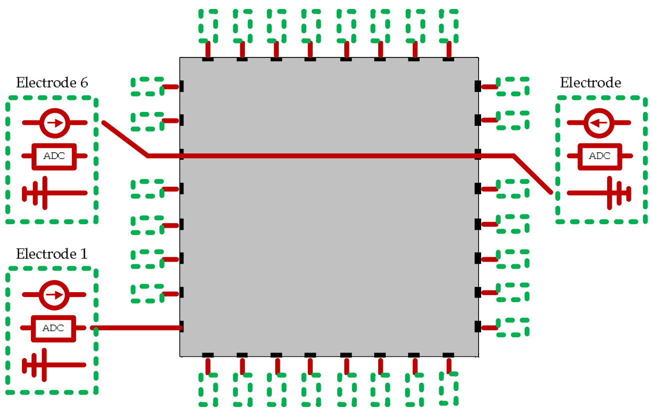
Voltage data from ADCs





Saving Data

- Voltage data format
  - Each column are the voltage measurements from one current injection
  - Number of columns indicates the number of current injections
- Send data to LAN or MicroSD Card
- Save data as a CSV-file



\# of Current Injections

19

$$\text{Measurement Data} = \begin{bmatrix} NaN & \cdots & V_1 & \cdots \\ V_1 & \cdots & \vdots & \cdots \\ \vdots & \cdots & V_5 & \cdots \\ V_{23} & \cdots & NaN & \cdots \\ NaN & \cdots & V_7 & \cdots \\ V_{25} & \cdots & \vdots & \cdots \\ \vdots & \cdots & V_{18} & \cdots \\ \vdots & \cdots & NaN & \cdots \\ \vdots & \cdots & V_{20} & \cdots \\ \vdots & \cdots & \vdots & \cdots \\ V_{32} & \cdots & V_{32} & \cdots \end{bmatrix}$$

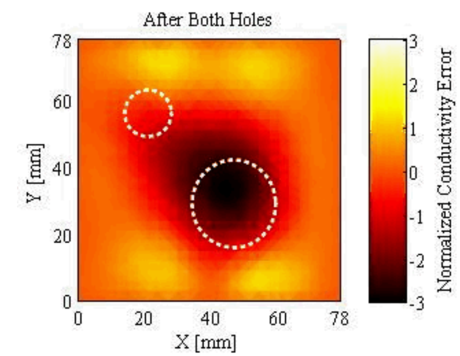
\# of Voltage Measurements

Inputs → Input Parser → Measurement → Data Management → Saving Data → Reconstruction

Reconstruction

- Conductivity reconstruction
  - Will be provided necessary MATLAB code
  - After measurements, will automatically process voltage data and reconstruct conductivity distributions
    - Software should ask for an initial baseline measurement for difference imaging
    - This could also just be an optional post-processing component of the software

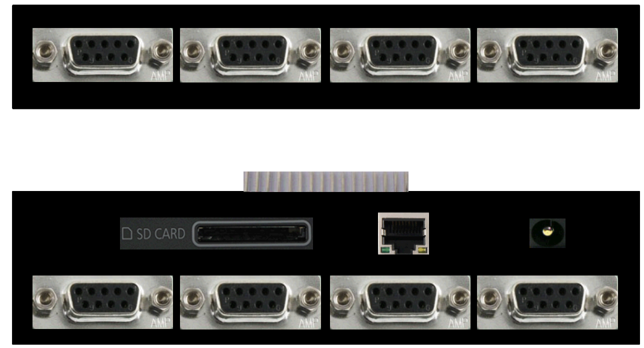
$$\begin{bmatrix} NaN & \cdots & V_1 & \cdots \\ V_1 & \cdots & \vdots & \cdots \\ \vdots & \cdots & V_5 & \cdots \\ V_{23} & \cdots & NaN & \cdots \\ NaN & \cdots & V_7 & \cdots \\ V_{25} & \cdots & \vdots & \cdots \\ \vdots & \cdots & V_{18} & \cdots \\ \vdots & \cdots & NaN & \cdots \\ \vdots & \cdots & V_{20} & \cdots \\ \vdots & \cdots & \vdots & \cdots \\ V_{32} & \cdots & V_{32} & \cdots \end{bmatrix}$$

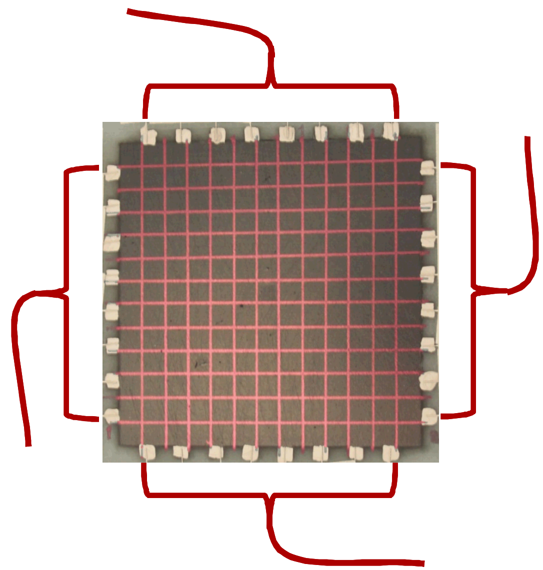


Inputs → Input Parser → Measurement → Data Management → Saving Data → Reconstruction

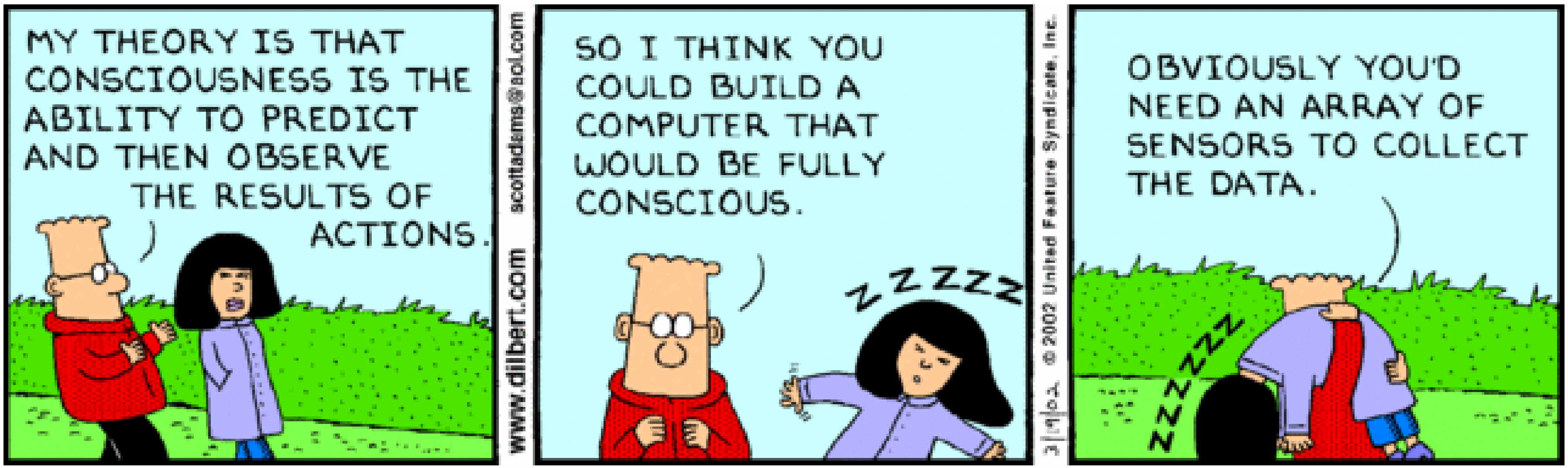
DAQ Unit

- Base station
  - All data compilation
  - Data collection
    - LAN
    - Memory card
  - 32 electrode nodes onboard
    - 4 8-pin connectors
    - Could be D-Sub 9 or the like
      - 1 empty pin
    - Could also be a D-Sub 32 pin or close and then use a breakout box closer to test article
  - Connector to expansion cards
  - DC Power – 12V?





Programmatic Stuff….



(http://dilbert.com/strips/comic/2002-03-19/)

High-Level Requirements

This project has three goals:

- Enable parallel voltage measurements during each current propagation
- Allow for a 32 electrode EIT measurement (896 voltage measurements) in less than 1 second.
- Interface the data acquisition unit with a GUI in MATLAB or an open source software package.

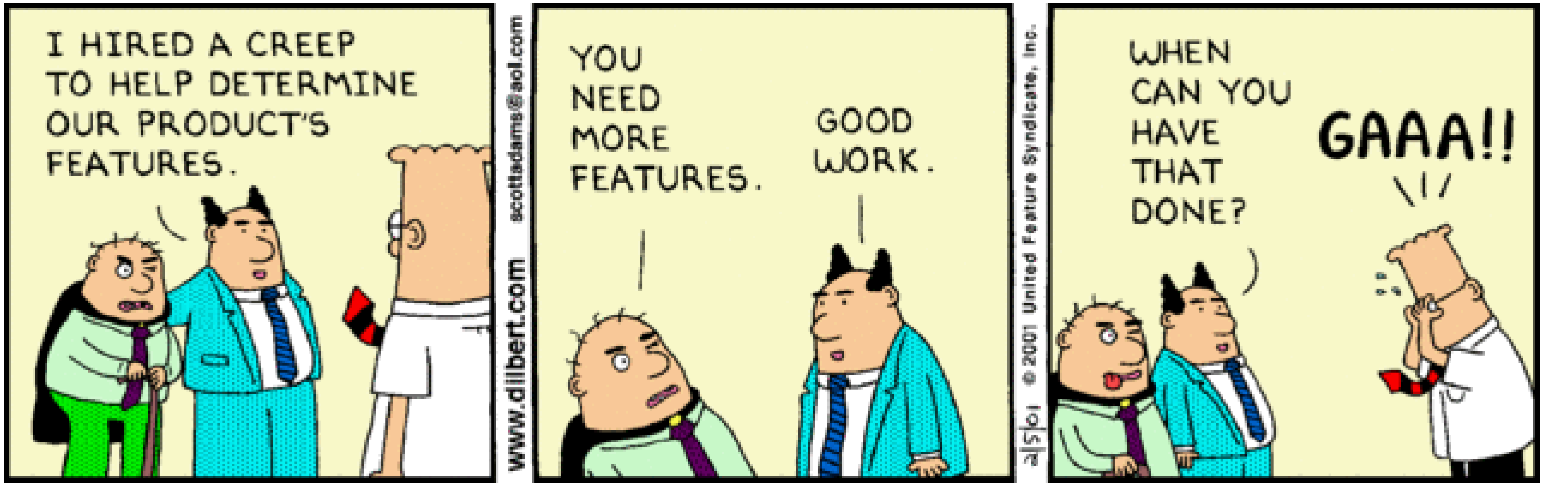
These requirements must be satisfied, and all lower-level requirements must be derived from these. Requirements are open to negotiation.

Required Deliverables

Sandia National Laboratories

- A turn-key box for taking EIT measurements on 32 electrodes
- Drawings, circuit diagrams, parts lists, etc. needed to make more
- Report and additional documentation required for your classes

These requirements must be satisfied, and all lower-level requirements must be derived from these. Requirements are open to negotiation.



(http://dilbert.com/strips/comic/2001-02-05/)

(http://dilbert.com/strips/comic/2001-02-06/)

Desired Goals

- Creating a stackable architecture enable the easy addition of measurement ports in sets of 16 or 32
- Take 100 samples per second (100 Hz)
  - Can you go higher?
- Adding a current meter in series with each current source for active current monitoring
- Capability to do four-point resistance measurements

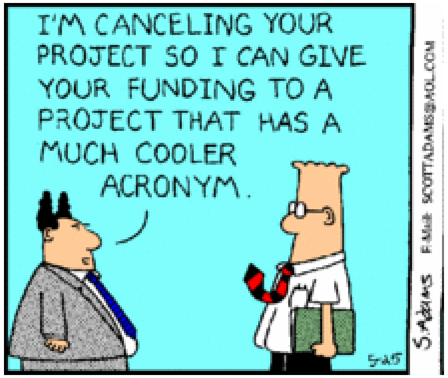
Desired Deliverables

- Box has capability to add additional modules
- Box comes with additional modules (plus drawings, documentation, etc.)
- Box can take four-point measurements (or a separate box that can take four-point measurements)

Desired Deliverables

- A clever acronym
  - Data Acquisition Module for Impedance Tomography (DAMIT)
  - Data Acquisition Module for EIT (DAME)
  - Daq of Electrical Current stimulated Electrical Impedance Tomography (DECEIT)
  - Daq Electrical Impedance TomographY (DEITY)
  - System Only Built for Electrical Impedance Tomography (SOBEIT)
  - System Of/Behind Electrical Impedance Tomography (SOBEIT)

  - Other words you could use include Utah, Sandia, Clinic, Box, Node, etc…



(http://dilbert.com/strips/comic/1994-05-25/)

Key Dates

- Mar 20 -- Kick-off meeting
- Apr 11 – Follow-up meeting (Technical Open House)
- Sept 24 – First design review (Career Fair)
- Dec 2*– Second design review
- Feb 4 – Prototype demonstration and final design review (Career Fair)
- Apr – Final demonstration and evaluation (Technical Open House)
- Additional meetings by phone, Skype, or in-person as desired as needed

* with changes as required to accommodate class requirements

Milestones

- Requirements & functional analysis, system architecture design, identify risks, develop project plan

First design review (Sept 24)

- Design, prototype, fabricate/load boards, program, etc.

Second design review (Dec 2)

- Integration, revision, testing, validation, documentation

Final design review (Feb 4)

- Finish testing, documentation

Technical Open House (Apr)

First Design Review (Sept 24)

- Objectives
  - Propose and present the project
  - Convince audience of feasibility given constraints of time, effort, and materials
  - Demonstrate project has appropriate complexity

- Should address the following
  - Outline of approach: block diagrams, ideas for architecture
  - Implementation of subsystems: how to realize
  - Division of labor, responsibilities, communication
  - Schedule: project milestones
  - Risks: areas of risk, mitigation plans

- Should be able to answer questions like:
  - What does the system do?
  - What does it look like?
  - How will it be used?

Second Design Review (Dec 2)

- Objectives
  - Present the design of the system and how it will be implemented
  - Ideas should be concrete at this point, moving out of prototype stage (85%)
- Should address the following
  - Block diagrams with functional description of parts and interfaces
  - Layout of circuit boards, parts, and mechanical interfaces
  - Complete specification of subsystems: circuit, logic diagrams, pinouts, interfaces with other systems
  - Test results and demonstrations of completed parts of the system
  - Parts list, bill of materials
- Should be able to answer specific questions:
  - How much power does it consume?
  - How much space does it occupy?
  - How much does it cost?

Final Design Review (Feb 4)

- Objectives
  - Fully describe the implementation and function of the system
  - Demonstrate a working prototype or final product
- FDR should address the following
  - All items required in PDR (block diagrams, circuit board layouts, etc.)
  - Test results and demonstration of complete, integrated system
  - Remaining work: what needs to be finished, fixed, refined, etc.
- Should be able to answer specific questions:
  - Over what distance does the wireless network function?
  - What range and sensitivity can each sensor detect?
  - What would be the path forward if the project were to continue?

http://dilbert.com/strips/comic/2007-04-12/

Recommended Path

- Develop a system architecture and paper design
  - Done by April 11 for discussion
  - Much of this is needed for your writing class anyway
  - Budget, schedule, division of tasks…

Division of Tasks

- System architecture
- Circuit design and component selection (e.g., ADCs)
- Controller
- PCB layout/fabrication
- Power supply & conditioning
- Data transfer (LAN, memory, etc.)
- Connectors and cables
- Packaging

Budget & Resources

- $3,000 through the clinic program
- We can arrange for loan of equipment if necessary

- How much will it cost to buy components?
- How many iterations can you afford to build?
  - Include final deliverable and desired expansion modules

- Current setup cost $8k
  - Can you build one for $1k? $200?

Budget Considerations

- Ideas for saving development costs
  - Make first prototype with smaller number of nodes (8?)
  - Design to allow for re-use of expensive parts (expensive parts on daughterboards?)
  - Can you make anything yourselves instead of buying?
  - Ask for samples from manufacturers
  - Student licenses (EAGLE, MATLAB, LabView) and discounts
  - DigiKey, SparkFun…

http://dilbert.com/strips/comic/1989-05-11/

PCB Layout And Manufacture

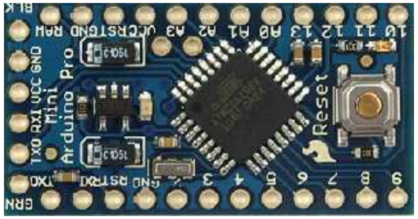
- Layout in EAGLE
  - Used by previous clinic groups (may still have licenses)
- Send out for fabrication
  - Suggestions:
    - http://www.sunstone.com/
    - http://www.4pcb.com/ (student program)
    - http://www.expresspcb.com/
    - http://www.pcbexpress.com

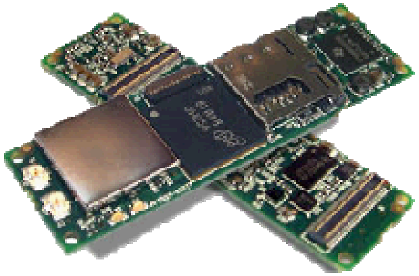
PCB Hints

- Expect to need multiple iterations as design matures and mistakes are found (e.g., pin layout was upside-down)
- Start learning EAGLE now, and get something made as soon as possible
  - Prototype with 8 nodes; or four-point measurements
- Hint: “0 ohm resistors” and test points are great for debugging!
- Hint: Can you squeeze multiple prototype designs on one board?

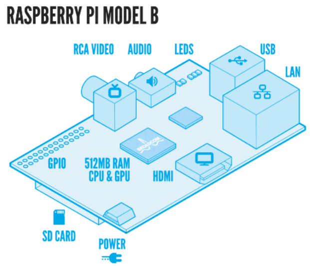
Controller

- Arduino
  - Open-source electronics prototyping platform
  - Simple, powerful, supported
  - Easy to use, active online community
- Gumstix (Overo series)
  - Small computer with built-in high-level functionality, such as 802.11b/g, Bluetooth
- Raspberry Pi
  - Like Gumstix and ~$35
  - Look into Alamode for more pinouts





https://www.gumstix.com/store/product_info.php?products_id=267



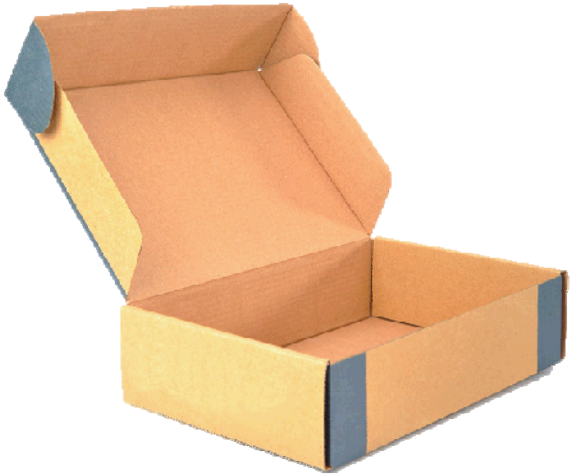
http://www.raspberrypi.org/faqs

Packaging Suggestions

- Won't need to worry for awhile…
- Minimize mechanical design
- Cardboard box, project box from Radio Shack

(Advanced)

- Make from acrylic
- Housing from 3D printer



http://www.radioshack.com/family/index.jsp?categoryId=2032276

Think About…

- How will it be used?
- What does user provide?
  - Input file with number of nodes and specified pairs of electrodes to be used for current injection
- What does user get?
  - Data saved in desired format (.csv?)
  - Reconstruction results saved as image

Schedule

(If you want to succeed…)

- Find a way to work on it over the summer (part-time)
- Work with a sense of excitement and urgency
- Earn your $1000 scholarship
- Have a goal to be DONE by early December, with *at least* 3-4 design iterations and PCB versions
- Talk to Dr. Schmid regularly
- Ask questions early and often

Schedule

(If you want to fail)

- Don’t do anything over the summer (because work, vacation, etc. don’t make it possible
- Or spend the summer confused and stalled, without asking questions
- Have no momentum when you come back in September
- Be used to making excuses that classes, work, tests, etc. are higher priority
- Besides, you still have plenty of time to get it done
- Order your first PCB in January, and maybe have something that (barely) works arriving in April

Other Random Tidbits

- Don’t overlook details like sample rates on ADCs
- On presentations, please use Sandia logo and CCAS logo
- Photographs of oscilloscope screens are great for a quick look, but not acceptable for formal presentations or documents
  - You may want to re-analyze the data later…
  - Make proper graphs with axis labels, units, etc.
  - Images should be credited (hypocritical me)
- Consider using Google groups or other arrangements for communications

Meanwhile…

- Weekly status reports
  - Simple memos, don't get bogged down in bureaucracy
  - Progress, decisions, what each person did
  - What you need from us

- Define project, negotiate requirements, work toward CDR
  - Open discussion

- Please include Steven AND Chris on all correspondence; include Bryan only if addressed specifically to him

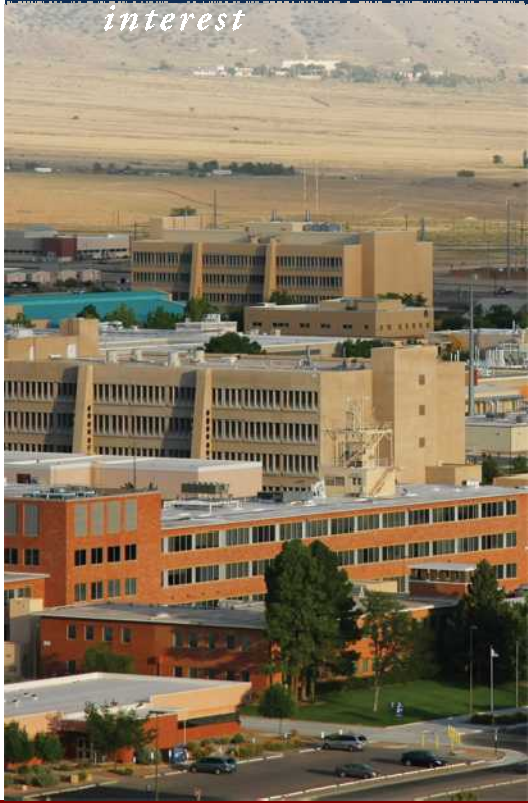
Contact Information

- Steven Paradise (programmatic)
  - sparadi@sandia.gov
  - 925.294.2755
- Chris Hall (technical – electrical)
  - chall1@sandia.gov
  - 925.294.3092
- Bryan Loyola (technical – EIT)
  - brloyol@sandia.gov
  - 925.294.6277

Thank You!

Sandia National Laboratories

Exceptional service in the national interest



Questions?

Acknowledgements:

Center for Critical Application Sensing @ Sandia National Laboratories