Overview & Highlights

Ming L. Wang
Director, VOTERS
Civil and Environmental Engineering
Northeastern University

This work was performed under the support of the U.S. Department of Commerce, National Institute of Standards and Technology, Technology Innovation Program, Cooperative Agreement Number 70NANB9H9012
Importance of Road Inspection

Condition of US roads is poor (unsafe)

Personal experience (local roads)

Professional organizations

Road inspections are needed for improvement

1. Spot and quantify all damage in a network
   — Can’t fix it if don’t know a problem exists

2. Map inspection results

3. Prioritize repair needs
   — Not enough resources to fix everything at once
Current Inspection Methods

Pavement Condition Index (PCI):
Manual inspection of 19 surface distresses

PCI Distress #1: Alligator Cracking

PCI Distress #11: Patching

Limitations of PCI
• Expensive
• Time consuming
• Traffic interruptions
• Subsurface not considered
• Periodic
• Small area of coverage
VOTERS Solution: Multi-Layered

Layer 1: Rapid Inspection
- Data acquisition (inside)
- GPS
- Optical
- Dynamic tire pressure
- Microphones
- MM-wave radar (underneath)

Layer 2: Detailed Inspection
- MASS cart
- GPR

Layer 3: Decision Making

Visit www.neu.edu/voters
Layer 1: Rapid Inspection

Vehicle (or vehicles) assess road conditions at driving speeds

Intended Functions

- Detect Pavement Design Type
  - SVM
- Estimate Mean Texture Depth (MTD)
  - Acoustic Energy method
  - PCA phase angle method (α)
- Estimate International Roughness Index (IRI)
  - Weibull distribution method (η, β, μw)
- Pavement Condition Index (PCI)

Future Goals

- Reduce sensor size and cost
- Field tests in areas of known PCI
- Autonomous operation
- Install on non-dedicated vehicles

Key VOTERS contributions

- Road condition rating
  - An index optimized for mobile sensing
- Provide alerts for troubled areas that need closer inspection in layer 2
Layer 2: Detailed Inspection

Highly detailed inspections are performed on troubled locations flagged in layer 1

MASS Vehicle

GPR

Hi-Res Video

Intended Functions

- Subsurface profile(layers)
- Modulus of elasticity(layers)
- Debonding/voids /moisture
- Rebar location
- Rebar corrosion
- Corrosion mapping
- Crack type and density
- Pothole
- Rutting
- Other surface distresses
Layer 3: Decision Making

Decisions are made based on mapped results of layers 1 + 2

Life Cycle Cost Analysis

Typical method: pavement performance curve is developed in design phase to approximate lifetime costs and repair schedule.

Intended Functions
- Identify need for immediate repairs
- Develop strategic long term maintenance plans
- Life cycle cost analysis - A continuous approach

VOTERS improvement: Use continuous monitoring to determine position on performance curve during lifetime, allowing repair schedule to be updated and optimized.
VOTERS Developing and Integrating Sensor Systems to Investigate Many Roadway Defects

Optical Surface Profile
- Rutting, Shoving, Cracking, Potholes

Acoustic
- Debonding, Voids, Stripping concrete
- Potholes, MTD, IRI

Subsurface Radar
- Rebar location, Delamination
- Rebar corrosion, Pavement thickness', Subsurface moisture, Voids

mm-wave
- Surface features
  - Water, Ice, Potholes, Surface roughness
  
Surface and Subsurface Sensing

Pavement
Sealing layer
Bridge deck

Tracking
Cracks
Potholes
Rebars
Corrosion and delamination

April 12th, 2012 | NIST site visit
www.neu.edu/voters
VOTERS Measurement Technology

VOTERS will develop new technology and adapt existing state of the art systems into an integrated, vehicle-based system to completely classify pavement condition while traveling at traffic speeds.

- **Ground Penetrating Impulse Radar**: Subsurface Defects like Corroded rebar up to one foot below surface. Also, map subsurface moisture.
- **Novel Acoustic Technology**: Using tire-induced vibration and sound waves to determine surface texture, and subsurface defects like debonded asphalt layers.
- **Optical Technology**: surface defects and sub-base health.
- **High-Frequency Radar**: Moisture content and Ice at surface and in the top 1-2 inches of pavement.
- Three pending and six provisional **patent applications** in the first three year of the program.
VOTERS COMPONENTS

GEARS

Radar Materials Characterization

SLiMR

SOPRA

BOSS

Data Registration
Onboard Processing
Supporting Sensor Systems

TEASe

MAP

www.neu.edu/voters
Roadmap

• Major hardware and software components were to be completed by 12/31/11.

• First phase systems Integration hardware and software component (such as BOSS, MAP, Data Registration) were to be completed and functional by 3/31/12.

• Go and no-go decision based on new budget constraint
Highlights

TEASe Objectives

• To detect surface conditions with running vehicle

• To detect surface/subsurface defects with running vehicle
TEASe Major Achievements

- Correlate Mean Texture Depth (MTD) to Acoustic Energy
- Differentiate Pavement Types by Support Vector Machine (SVM)
- Relate Pavement Surface Condition to Probability Density Function (PDF)
- Measure Surface Wave through Dynamic Tire Pressure Sensor (DTPS)
- Determine Subsurface Profile using Mobile Acoustic Subsurface Sensing (MASS) in a moving vehicle
- Develop Wireless DTPS system with energy harvesting capability
- Confirm acoustic radiation from the surface wave is significantly stronger than acoustic noise, enabling subsurface detection
VOTERS VEHICLE

System Integration

- Microphone array
- Accelerometer
- Laser distance sensor
- Infrared thermometer
- Dynamic tire pressure sensor
- GPS
- Video camera
- BOSS system
- DAQ

Northeastern

April 12th, 2012 | 14 | Y3 NIST site visit

www.neu.edu/voters
NCAT Test

46 sections
5 configurations
200 runs
50 GB data
Road Test Configuration Example

Data used for the analysis is collected by S5

Sampling rate: 40K Hz

Speed: 20mph
   35mph
   50mph

Example:
For one pavement
Time window: ≈0.2s

$2^{13}$ data length
ROAD TESTS
Pavement Identification Via SVM

How it Works

Create Patterns

[Sound Waves]

Contact Point

Superpave

Input Patterns to Pre-trained SVM Classifier

Prediction

{Superpave}

A machine learning algorithm with several advantages over its competitors:

- Better generalization
- No upper limit on # of features
- Works well even if training set is small

Results on NCAT Data

97.2% Accuracy (70/72)

Correct prediction
Incorrect prediction

Northeastern
The University of Vermont
UMass Lowell
Trilion

Sensor Systems
www.neu.edu/voters

April 12th, 2012 | 18 | Y3 NIST site visit
Acoustic Energy for MTD (Mean Texture Depth)

**Advantages**
- Real-Time
- Continuous
- Automatic
- Safe
- Reliable
- Accurate

**Disadvantages**
- Time consuming
- Dangerous
- Creates Traffic
- People dependent

**Conventional Sand Patch Method**

**0.8-0.9 Correlation**

**Correlation of Tire Noise to MTD**

![Graph showing correlation between tire noise and MTD](graph.png)

**SPL Amplitude (dB)**

- **50-600 Hz**
  - Optimal Spectrum Energy Range for MTD Measurement

**Energy (dB – Hz)**

- **run1 = 3605.2x + 28327**
  - \( R^2 = 0.2257 \)
- **run2 = 3233.9x + 28480**
  - \( R^2 = 0.7936 \)
- **run3 = 4044.8x + 27414**
  - \( R^2 = 0.9234 \)

---

Northeastern University

April 12th, 2012 | 19 | Y3 NIST site visit
Principal Component Analysis for Surface and Subsurface Analysis

What is PCA? — A statistical method for feature extraction from measured data

What’s the use? — Noise elimination

Where noise comes from?

![Image](Tire/road sound) Time variant noise

Current achievement
- MTD estimation
- Subsurface assessment

Future research
- A Mathematical model for real-time MTD estimation
- Subsurface layer identification
- Other principal components
- Statistical analysis

MTD estimation

- $\alpha = \text{phase angle between 1st PCs of tested pavement and known pavement.}$
- Large $\alpha (40^\circ)$ indicates large difference
- Small $\alpha (20^\circ)$ indicates small difference

Subsurface assessment

- Different 1st PCs at [600~1200] Hz, different subsurface profile.

Noise Elimination

Time history of sound measurements before and after PCA treatment
IRI Detection Using Probabilistic Approach

IRI (International Roughness Index) measures road roughness and indicates how comfortable riders feel in a moving vehicle at 80km/h.

Example: Comparison between Rough Road (Red) and Smooth Road (Blue) Original Data (Storrow Dr)

Signal processing: moving average, bandpass [3,50]Hz

Weibull Distribution

\[ f(x; \beta, \eta) = \frac{\beta}{\eta} \left(\frac{x}{\eta}\right)^{\beta-1} e^{-\left(\frac{x}{\eta}\right)^\beta} \quad \beta > 0, \eta > 0, x > 0 \]

\( \beta \): shape parameter; \( \eta \): scale parameter;

<table>
<thead>
<tr>
<th></th>
<th>Rough Road</th>
<th>Smooth Road</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \beta )</td>
<td>1.0738</td>
<td>1.1816</td>
</tr>
<tr>
<td>( \eta )</td>
<td>0.0053</td>
<td>0.0016</td>
</tr>
<tr>
<td>Mean (Pa)</td>
<td>0.0051</td>
<td>0.0015</td>
</tr>
<tr>
<td>IRI (m/km)</td>
<td>7.213</td>
<td>1.514</td>
</tr>
</tbody>
</table>
Dynamic Tire Pressure Sensor System (DTPS)

- Assess roadway surface conditions and detect subsurface delamination.
- Reconstruct ground vibration.
- Reconstruct road height profile/roughness through dynamic tire pressure change.

**Product Specifications**

1. Tire Pressure sensor
   - Frequency: 0.5 – 20 kHz
   - Static pressure: 0 – 50 psi
   - Dynamic pressure: 0 – 1 psi

2. Wireless transmitter
   - Sampling rate: 30 K Hz

3. Energy harvester
   - Average output power density of 1.5 W/cm² with different speed

- natural barrier to external noise
- ground vibration /acceleration amplifier
- instruments are protected from the environment

April 12th, 2012 | 22 | Y3 NIST site visit

Northeastern University, The University of Vermont, UMass Lowell, Trilion

Sensor Systems | www.neu.edu/voters
Surface-Looking mm-Wave RADAR

Overview/How it works
- millimeter-wave has 12.5 mm wavelength, investigates feature sizes to ~2 mm
- can use feature to determine and characterize material (‘fingerprinting’)
- goal to apply to road determination @ fast speed

Year 3 Achievements
- Version 1 complete prototype built and verified
- Version 2 high-power prototype assembled and tested
- Correlation between V.1 and V.2 material characterizations

Year 3 timeline

Data processing and algo

Version 1 - Hardware prototype

Version 2 – Compact high power option
System Integration

Objective:
• Facilitate constructing VOTERS from set of sensors
• Architectural framework for *Mobile Multi-domain Multi-OS Multi-tier Sensor System*
  – Continuous network-wide health monitoring of roadways and bridges
  – **Expandable** beyond its original project purpose

Achievements:
• Project management site gains traction
  – Version control (500+ commits)
  – Wiki (with videos!)
  – 78 ToDo, + Features, + Bugs
• Defined communication principles for:
  – Control messages
  – Autonomous messages
  – Bulk data handling
• CORBA-based communication scheme rolled out
  – 3/8 test run: MAP, BOSS, TEASE, DRS, SOPRA
System Integration

Achievements (cont’d):

- **Object Oriented design** encapsulates common behavior
  - Minimize work for new sensors / extensions
- **Timing synchronization within VOO**
  - Use SW instead of dedicated HW -> reduce $$$
- **Designed bulk data handling**
  - DATA Hierarchy: Survey, Session, Streams, Files
  - Operations: Plugins to operate collected data

Future Plans:

- Solidify MAP / ARCGIS communication
- Implement bulk data handling
- Implement framework for plugin system
  - Flexible transition between processing levels
    - Sensor: In time
    - BOSS: Time-delayed
    - MAP: Time-delayed post processing
- Provide common logging and debugging access
- Android Tablet for VOO control and status info
Layer 2: Detailed Inspection

Highly detailed inspections are performed on troubled locations flagged in layer 1

MASS cart

- Subsurface profile (layers)
- Modulus of elasticity (layers)
- Debonding/voids/moisture

GPR

- Rebar location
- Rebar corrosion
- Corrosion mapping

Hi-Res Video

- Crack type and density
- Pothole
- Rutting
- Other surface distresses

Intended Functions
Mobile Acoustic Subsurface Sensing (MASS) System for Real-time Pavement Condition Assessment

Objectives of MASS:
Convert the contact sensing to non-contact mobile sensing to estimate the pavement subsurface profile in real-time

Current Achievements:
• Working MASS prototype
• Mobile and real-time operation

Case Studies:

Asphalt Pavement
Concrete Floor

Approaches:
• Fast inversion algorithm
• Wave-number fitting

The comparison between microphone and accelerometer promised the non-contact sensing
GEARS

Small, Fast, and Low-cost
High-Frequency Ground Penetrating Radar (GPR) Array

UVM-GPR

GOALS:
• Low-cost transmitter (Dual band)
• High-speed single-shot sampling
• Very fast

STATUS:
• Started dual-channel distance-triggered field tests with pushcart

GEARS - Antennas

GOALS:
• Innovative air-coupled antennae design

UVM, ESS, and NEU team exploring and testing various manufactured antenna types and designs suitable for both systems

ESS-GPR

GOALS:
• Faster than any current COTS, but slower than UVM R&D goal
• Integration as array on VOO in year 4

STATUS:
• Started systematic field testing of ESS-GPR + NEU antennas in laboratory
Basic R&D – Radar Materials Characterization –

- Dielectric properties (complex permittivity, \( \varepsilon_r^* = \varepsilon_r' - \varepsilon_r'' i \)) of new and old concretes and iron oxide powders (rust, Fe\(_3\)O\(_4\), Fe\(_2\)O\(_3\))
- Accelerated corrosion test on RC slabs → A test bed for \textbf{SLiMR} and \textbf{GEARS} inspection and other NDT methods (e.g., GPR and HCP sensors)
RAV (Radar Analysis and Verification) Summary

- Objective – Detect subsurface conditions using GEARS
- Accomplishment – Developed relationships between GEARS data and bridge deck corrosion
- Plans – Verify results on in-service bridge decks in MA

GPR vs. Corrosion

Distribution shows Damage

Good deck

Deteriorated deck
SOPRA

Surface Optical Profilometry Roadway Analysis

SOPRA Video

GOALS:
• Streaming Video data collection, 100% coverage.
• CORBA communication interface.
• Video data reduction, with real-time processing.

STATUS:
• Basis operation on VOTERS Van with CORBA communication.

SOPRA 3D

GOALS:
• Streaming 3D video data collection, 100% coverage
• Non-interfering near-IR illumination
• 2mm resolution

STATUS:
• Production Prototype has run on VOTERS Van.

MAP Image Analysis

GOALS:
• Post-processing of SOPRA video images for:
• Road surface visual measurement
• Video registration

STATUS:
• Preliminary 3D data analysis, crack detection, anomaly determination and sizing

April 12th, 2012 | 31 | Y3 NIST site visit
Layer 3: Decision Making

Decisions are made based on mapped results of layers 1 + 2

Intended Functions

- Identify need for immediate repairs
- Develop strategic long term maintenance plans
- Life cycle cost analysis
  - A continuous approach

Life Cycle Cost Analysis

Typical method: pavement performance curve is developed in design phase to approximate lifetime costs and repair schedule

VOTERS improvement: Use continuous monitoring to determine position on performance curve during lifetime, allowing repair schedule to be updated and optimized.
Management And Prognosis (GIS System)

Central Data Collection

GOALS:
- Data monitoring and control of VOTERS vehicles
- Data collection and storage

STATUS:
- Core real-time communication established and functional using CORBA and IIOP.Net standards
- Bulk data transfer and storage is operational via FTP

Data Analytics: ePCI

GOALS:
- Enable real-time and historical analytics for each specific sensor
- Merge & compare multiple sensor data types to calculate higher level condition parameters

STATUS:
- Preliminary analytics plug-in for crack detection analysis

Geo Information System

GOALS:
- Web client for real-time and historical infrastructure spatial data management
- Empower video wall with thin client GIS viewer

STATUS:
- Completed, using ArcGIS Server technology, with custom thin client Microsoft Silverlight Viewer
Video Processing

- **Goal**: Model a fully automated algorithm to detect every surface defect (potholes, rutting, raveling, all types of cracking etc.) and quantify the defect severity.

- **Achievements**:  
  **Blending Images**:  
  - Feature based fully automated blending algorithm is implemented based on corner detection, non-max suppression and RANSAC followed by homography calculation.  
  - An example of Forsyth Street is shown in maps.  
  **Crack detection using a probabilistic model**:  
  - Distortion correction algorithm followed by multiclass logistic classifier is used to classify the results into different types of cracks.  
  - The detected cracks can be classified as alligator cracking, block cracking, longitudinal cracking or transverse cracking for calculation of the PCI index.

A layer of 40 high resolution gray scale images of the Forsyth street, Boston, MA, is placed on Google maps using its GPS co-ordinates. Images with overlap have been blended into a single image layer.
## VOTERS Meeting Schedule

### Fall 2011

<table>
<thead>
<tr>
<th>Monday</th>
<th>Tuesday</th>
<th>Wednesday</th>
<th>Thursday</th>
<th>Friday</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radar</td>
<td>10:30</td>
<td>9:30 BOSS</td>
<td>10:00 Research Grp</td>
<td>10:00 Research Grp</td>
</tr>
<tr>
<td></td>
<td>2:00 RAV</td>
<td>1:00 TEASe</td>
<td>11:00 Staff</td>
<td>11:00 Staff</td>
</tr>
<tr>
<td></td>
<td>4:30 SLiMR</td>
<td>3:00 SI Architects</td>
<td>1:00 MAP</td>
<td>1:00 MAP</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4:00 ASG(monthly)</td>
<td>Nano 3:30</td>
<td>Nano 3:30</td>
</tr>
</tbody>
</table>

- **Radar (bi-weekly)**: Ralf Birken, Dan Busuioc, Dryver Huston, Ken Maser, Ming Wang, Tian Xia, Ming Li, Anbu Venkatachalam, Chuck Oden, Xianlei Xu, TzuYang Yu, Nian Sun, Ming Wang, Kim Belli, Reid Vilbig, Patrick Thompson, Xianlei Xu,

- **BOSS (bi-weekly)**: Ralf Birken, Dave Hastings, Jiaxing Zhang, Yi Zhang, Steve Zhu, Gunar Schirner, Ming Wang. Patrick Thompson, Ralf Birken, Jennifer Dy, Ming Wang, Yingying Wang, John Tyson


- **MAP (bi-weekly)**: Ralf Birken/David Hastings/Sara Wadia-Fascetti, Ken Maser, Steve Zhu, Sindhu Ghanta, Xin Ma, Patrick Thompson, Ralf Birken, Jennifer Dy, Ming Wang, Yingying Wang, John Tyson

- **Data Registration Strategy (DRS) (scheduled as needed)**: Ralf Birken, Jiaxing Zhang, Yi Zhang, Ming Wang

- **SLiMR (bi-weekly)**: Dan Busuioc, Ralf Birken, Ming Wang, David Vines-Cavanau, Ming Li, Reid Vilbig

- **VOTERS Staff (weekly)**: Ming Wang, Ralf Birken, Sara Wadia-Fascetti, Veena Teli, Yi Zhang

- **JV Partner Mgmt. Mtg (sch. monthly)**: Ming Wang, Veena Teli, Dryver Huston, Chuck Oden, John Tyson, Sara Wadia-Fascetti, TzuYang Yu

- **Acoustic Sensor Group (ASG) (monthly)**: Ming Wang, Nian Sun, Ralf Birken, Qi Wang, Yu Liu, Wenjun Zhang, Yi Zhang

- **TEASe (weekly)**: Ming Wang, Yifeng Lu, Greg McDaniel, Qi Wang, Yiyin Zhang, Xin Ma, Yubo Zhao, Nian Sun, David Vines-Cavanau

- **Nano Sensor Meeting**: Ming Wang, Ralf Birken, Wenjun Zhang, Yiyin Zhang, Yunqing Du

- **Research Group**: Ming Wang, Ralf Birken, Xin Ma, Reid Wilbig, Nicole Martino, Sindhu Ghanta, Ming Li

*Group Leader* is expected to provide an agenda (with meeting objectives) to all members before each meeting and is responsible for editing and distributing meeting minutes taken by a student. Webex access can be arranged as needed through Veena.