Emerging Trends in Sensor Technology: Sensors and Instruments for the Future

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The findings and conclusions in this presentation are those of the author and do not necessarily represent the views of the National Institute for Occupational Safety and Health. Mention of company names or products does not constitute endorsement by NIOSH.
The Future of Sensors: for anything, anywhere, everywhere

- Wearable Technology
- Embedded Sensors
- Smartphone Apps
- Sensor Arrays
- Self-powered Arrays

http://habitatmap.org/markers
NIOSH Center for Direct Reading and Sensor Technologies

Enabling safety, health, well-being, and productivity

www.cdc.gov/niosh/topics/drst/
How do we define and advance the life-cycle for Turning Numbers into Knowledge?
Figure 1. Life-cycle stages for development and application of sensors.

Source: A Life-Cycle Approach for Development and Use of Emergency Response and Health Protection Instrumentation.
OUR OVERALL OBJECTIVE

Build and sustain leaders, cultures, and systems for safety, health, well-being, and productivity
# A Perspective from Sensors developed by Evolution for Safety and Survival

<table>
<thead>
<tr>
<th>Biological Sensor</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sight (dark-adapted eye)</td>
<td>10 photons/sec-cm²</td>
</tr>
<tr>
<td>Infrared (snake)</td>
<td>$10^{-4}$ W/cm² @ 300 K</td>
</tr>
<tr>
<td>Acoustic (ear)</td>
<td>0.5-angstrom vibrations</td>
</tr>
<tr>
<td>Electric field (fish)</td>
<td>$10^{-2}$ $\mu$V/m</td>
</tr>
<tr>
<td>Displacement (scorpion)</td>
<td>1 angstrom</td>
</tr>
<tr>
<td>Smell (moth)</td>
<td>1 molecule</td>
</tr>
<tr>
<td>Ultraviolet radiation (bird)</td>
<td>$10^{10}$ photons/sec-cm²</td>
</tr>
<tr>
<td>Seismic (frog)</td>
<td>1 micro-g</td>
</tr>
<tr>
<td>Magnetic (pigeon)</td>
<td>$10^{-2}$ gauss</td>
</tr>
<tr>
<td>Smart sensor (frog's eye)</td>
<td>algorithms for array processing, edge enhancement, and changing contrast (i.e., “on-chip” processing)</td>
</tr>
</tbody>
</table>

Adapted from a slide kindly provided by Ernest Streicher of John Deere
Helmet CAM and EVADE software

Personal monitoring system comprised of a helmet mounted video camera and a continuous real time dust monitor.

**Target** - Mobile workers  
**Goal** - Evaluation tool to determine “sources of exposure” and “control technology effectiveness”.

**Applications** – Respirable dust, Noise, Diesel Particulate Matter, Chemical compounds

Workers did not consistently stand atop the tank to gauge. Gauging from the ladder platform resulted in higher exposures.
Aerosol Spark Emission Spectrometer (ASES)

• ASES can measure simultaneously measure almost all metals at LOD of ~1 µg/m³ with about 1 min time resolution

• Features:
  – Hand-portable, < 8 lb
  – Battery-operated, stand-alone continuous operation
  – Can simultaneously measure most metals of interest
  – LOD~1 µg/m³ at ~1 min collection for most metals
  – Allows continuous mobile measurements, personal exposures
Measurement of Welding Aerosol Using ASES

Diagram showing the path from Indoor Office Environment to Welding Shop and Welding booth.

Graph showing concentrations of Fe, Mn, and Cr over time with OEL levels for Fe, Mn, and Cr.
Measurement of Welding Aerosol Using ASES

Walking in clean office environment

Walking in welding area; welding off

Walking in workshop with welding operation on

Walking away from welding area

$\frac{dN}{d\log D} (\text{cm}^{-3})$

- 4.7E+07
- 1.3E+07
- 3.8E+06
- 1.1E+06
- 3.0E+05
- 8.6E+04
- 2.4E+04
- 6.9E+03
- 2.0E+03
- 5.6E+02
- 1.6E+02

Diameter (nm)

20 50 100 150 250 350 450 550 700 800

Time (s)

500 1000 1500 2000 2500

Department of Health and Human Services
Centers for Disease Control and Prevention
National Institute for Occupational Safety and Health
Nanoparticle Monitors

- Size range: 15 – 633 nm
- Resolution: 8 channels per decade (13 channels total)
- Measurement time: 30-50 s
- Dynamic range: 1-10^5 particles/cm^3
- Total flow: 0.7 lpm
Personal Dust Monitor (PDM)

- The PDM **continuously** monitors the worker’s personal exposure to respirable dust and it displays cumulative, current (i.e. last 30 minutes) and shift limit information in numeric and graphical formats.

- **At the end of the shift**, the PDM provides a true mass measurement of the dust collected. The data are automatically converted into average shift respirable dust concentration.

- The real time data stored in the instrument can be downloaded and analyzed at the end of the shift. The data can be used for identification of dust sources, optimization of mine ventilation or control technologies.
Coal Dust Explosibilty Meter (CDEM)

Allows for immediate identification and mitigation of an area deficient in rock dust – rock dust is needed in coal mines over coal dust to mitigate the risk of explosion.

Accounts for the particle sizes of the coal and rock dust.

Based on:

- optical reflectance
determines the ratio of rock dust to coal dust surface area (% RD)

- full-scale experiments on flame propagation

- use of well mixed and dry dust mixture

For more in-depth information: Coal Dust Explosibility Meter Evaluation and Recommendations for Application. NIOSH [2012].

http://www.cdc.gov/niosh/mining/Works/coversheet1843.html
Proximity detection systems are required to protect miners near continuous mining machines (MSHA rule).

Conventional systems stop machine motion completely when a person is detected in the danger zone.

The NIOSH-developed system only disables potentially dangerous motions.

This allows the operator to:

- Avoid other hazards
- Better see necessary visual cues
- Minimize nuisance alarms
Positioning System Coupled to a Personal VOC Exposure Monitor

RF positioning tag

Micro Temperature And Humidity Sensor

Micro Volatile Organic Compound Sensor
Methamphetamine Test Kits

Two Direct Reading Methods: Colorimetric and Immunochemical
Licensed to SKC as “MethAlert” “MethChek”
Methamphetamine Test Kits

Control Line  Test Line  Sample Port

NEGATIVE TEST

POSITIVE TEST

2 cm  7 cm
Development and Validation of a Wearable, Real-time Ultraviolet Native-Fluorescence-Based Monitor
NaDOS Anatomy

- Native fluorescence of molecules excited by pulsed UV light (280-320 nm) to perform qualitative and quantitative analysis.
- Air enters sample chamber and the compound is concentrated and exposed to UV light.
- The UV light excites the molecules of the gas or vapor and the molecule emits a compound specific-spectral signature.
- The emitted signal strength corresponds to the chemical concentration.
Emission spectra for most organics is limited to wavelengths above 260 nm.
NaDOS Chemometric comparison

Y axis is the ratio 320/340 and the x axis is 340/360. Notice the tight cluster of the ratios for an individual chemical compared to the large spread on the axis. All of these chemicals are easily differentiated.
Laboratory Validation

Develop methods for delivering known concentrations of naphthalene to the NaDos, PID and Gas Chromatograph to reach the goal of detecting and identifying naphthalene vapor densities as low as 100 µg/m³ and as high as about 1.5 g/m³ in a time period of about 2-3 minutes.
Field Validation

Data Collection Conducted
US military base locations
(Army and Air Force)

Working with warfighters
working different job
types: fuel cell (5), POL (4),
vehicle mechanics (3),
refuelers (2), helicopter
crew chief and pilots (2)
NIOSH Sound Level (SLM) Meter App

- Study on smartphone sound meter apps examined accuracy and functionality of 192 iOS and Android apps
- 4 iOS apps had mean differences within ± 2 dBA w/SLM
- NIOSH SLM App based on tech from one of the 4 apps developer
- Available for free – Worker empowerment, job exposure database, calibrated in our labs
- Currently in beta testing – Not yet approved for distribution
Use w/ External Mic (Type 2)

Significant Advantage: Ability to calibrate app using regular acoustic calibrators!
Noise App Impact and Challenges

• Adoption of more smartphones = 
  A noise dosimeter in every pocket

• Better **worksite management** and occupational safety and 
  health **staff involvement**

• Residents’ and citizens’ **awareness** of noise pollution leads 
  to better **involvement** of city planners and regulators.

• **Buying and using quieter equipment**

Challenges remain: Accuracy, privacy, corrupt data, data 
storage, calibration standard
A Convergence for Information Sharing

Safety, Health, Well-being, and Productivity

New Technologies

Risk Management

Focus on the Convergence = Focus on Success.
The “I”s are in the eye of the beholder.

One size does not fit all...
Specific messaging and actions in each element of the matrix must be based on (a) what knowledge and understanding each stakeholder needs and (b) what knowledge and understanding each stakeholder can provide.
Informatics Roles and Responsibilities

Communication and understanding are essential at all steps.
The IH Decision-making Framework and Process

Anticipate and Recognize  ➔ Evaluate  ➔ Control and Confirm Protection

Constant communication, continuous improvement

Risk Assessment

**Hazard Assessment**
Identify and define dose-response relationships and "Hazard Criteria"
- Occupational Exposure Limits
- Skin Notations, ...
- Hazard Bands

**Exposure Assessment**
Collect all "relevant and reliable" exposure information for assessment against and refinement of the "Hazard Criteria"

**Risk Characterization**
Characterize risks associated with "realistic" combinations of hazards and exposures

**Risk Management**
Use the Hierarchy of Controls to apply "appropriate" controls and programs and confirm protection
Assessments of risk are likely to be valid. Exposure-associated hazards may not yet be known. Hazard assessments may not be relevant to actual exposures. Hazards, exposures, and resulting risks are poorly understood.

Key ingredients:
- Hazard-Informed Exposure Assessment
- Exposure-Informed Hazard Assessment

Draft for discussion – adapted from Hoover et al., 2015
Nanotechnology Signature Initiatives

• Nanotechnology for **Solar Energy Collection and Conversion**

• **Sustainable Nanomanufacturing**: Creating the Industries of the Future

• **Nanoelectronics** for 2020 and Beyond

• Nanotechnology **Knowledge Infrastructure**: Enabling National Leadership in Sustainable Design

• Nanotechnology for **Sensors and Sensors for Nanotechnology**: Improving and Protecting Health, Safety, and the Environment

• Related initiative: **Materials Genome Initiative**
Our Premise:
We can accelerate discovery, revolutionize design, and sustain innovation through a Knowledge Infrastructure.

Grass roots involvement is required!
Some Components of the NKI

GitHub

- MaterialsHUB
- Interatomic Potentials Repository Project
- OpenKIM
- nanoHUB
- Nanoparticle Information Library
- XSEDE
- GoodNanoGuide
- caNanoLab
- NANOMATERIALREGISTRY
- Applications of Nanotechnology for Safe and Sustainable Environmental Remediations
- ANnsERs

- Supported by NIH, NIOSH, NIST, NSF, ONR, DOE, EPA …

A wide array of nanoinformatics activities are already underway.
## Data Readiness Levels

### Summary of DRLs Versus Data Attributes

<table>
<thead>
<tr>
<th>Attribute</th>
<th>DRL 0</th>
<th>DRL 1</th>
<th>DRL 2</th>
<th>DRL 3</th>
<th>DRL 4</th>
<th>DRL 5</th>
<th>DRL 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Units</td>
<td>maybe</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Precision and Noise</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Expected to be either</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Independent Confirmation</td>
<td>possibly</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Related to Larger Body of Scientific Knowledge</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measurement Uncertainty</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Expected to be speculative</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Related to larger body of knowledge</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Example or use</td>
<td>little to none</td>
<td>unscaled sensor data</td>
<td>scaled sensor data</td>
<td>scaled data; noise levels defined</td>
<td>major scientific advances</td>
<td>coarse validation of theory</td>
<td>theory refinement and methods validation</td>
</tr>
</tbody>
</table>

Data attribute details are application-dependent.
Four Steps for Community Action
to build and sustain leaders, cultures, and systems for safety, health, well-being, and productivity

Thank you for partnering with us for success.
# Steps to Data Readiness for Decision-Making

<table>
<thead>
<tr>
<th>Step</th>
<th>Attribute</th>
</tr>
</thead>
<tbody>
<tr>
<td>00</td>
<td>Establish CLEAR objectives</td>
</tr>
<tr>
<td>0</td>
<td>Address uncertainty</td>
</tr>
<tr>
<td>1</td>
<td>Address false positive conclusions</td>
</tr>
<tr>
<td>2</td>
<td>Address false negative conclusions</td>
</tr>
<tr>
<td>3</td>
<td>Apply appropriate decision levels</td>
</tr>
<tr>
<td>4</td>
<td>Apply appropriate evaluation methods</td>
</tr>
<tr>
<td>5</td>
<td>Differentiate correlation from causation</td>
</tr>
<tr>
<td>6</td>
<td>Apply appropriate extrapolations</td>
</tr>
<tr>
<td>7</td>
<td>Develop adequate documentation</td>
</tr>
<tr>
<td>8</td>
<td>Address mishap or misconduct</td>
</tr>
</tbody>
</table>

*Focus on doing the right things right.*

Adapted from Hoover et al., 2014
Focus of the NIOSH Sensor Center

• **Coordinate a national agenda** for direct-reading methods and sensor technologies

• **Develop guidance** documents pertinent to direct-reading methods and sensors, including validation and performance characteristics

• **Develop training protocols**

• **Establish partnerships** to collaborate in the Center’s activities

Thank you for partnering with us for success.
Questions?

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References


