Low-power Pulse Oximetry

Dr. Alper Bozkurt and Dr. Michael Daniele
NC State University
Pulse Oximetry: A Power Hungry Process

GEN-0
commercial off the shelf device based system

- ECG (0.5 mW)
- Accelerometer (0.06 mW)
- Pulse Ox (15 mW)
- Microphone (0.35 mW)
- System on Chip (11.5 mW)
- Hydration (36 mW)

- Accelerometer (0.06 mW)
- Ozone Sensor (102 mW)
- Pulse Ox (15 mW)
- Humidity/Temp Sensor (0.45 mW)
- System on Chip (11.5 mW)
- Wrist Band
Pulse Oximetry Architecture Optimization

- Monolithic TIA
- Duty cycling
- Energy Harvester
- Compressed sensing
- Micro Controller
- Accelerometer
- WiFi
- BlueTooth LE
- AFE
- Photo diode
- Tissue
- LED
- Multi-junction or organic devices
- Anti-reflective coating
- Wavelength selection
- Tissue-device coupling modelling
- Duty cycling
Year 6 roadmap and progress

Integration of the ultra low power PPG ASIC into HET

Design and manufacturing of an ultra-low power organic photodevice based wearable pulse oximeter system
PPG ASIC (in collaboration with imec)

• Ultra-low power highly integrated PPG readout ASIC
  ▪ Compressive sampling based acquisition
    ➔ Upto 30x reduction in LED driver power consumption
  ▪ Integrated digital back end for feature extraction
    ➔ Heart rate extraction directly from compressively sampled PPG signal without reconstruction
    ➔ Wide heart rate range (30-210bpm) with 3bpm resolution
  ▪ IC fabricated, tested and published. Inclusion into testbed in progress..

IEEE Transactions in Biomedical Circuits and Systems, 2017
Compressive Sampling reduces LED power proportional to Compression Ratio (CR = N/M) (8x, 10x and 30x).

**Challenges** – Signal/Feature recovery

**PPG ASIC System Architecture**

PPG front-end with compressed sensing capability and 8-bit successive-approximation register (SAR) ADC with charge-redistribution DAC.
PPG ASIC Overview

- 4.0mm x 2.5mm, 180nm CMOS process
  - 1P6M, 8kATM, 2fF/µm² MIM, HRP
- 1.2V operation

![Image of ASIC with components labeled: DECAP, SC-LPF, DECAP, BIAS, TIA, SAR, ADC, Digital Logic, DMEM1, DMEM0, and a power consumption graph showing 1x, 6x, 10x, 30x compression ratios.]

- Power Consumption [µW]:
  - AFE: 7.2µW
  - DBE: 6µW
  - ADC: 158.8µW

![Images of oscilloscope and circuit board demonstrating operation and performance metrics.]
## PPG ASIC Performance Benchmarking

<table>
<thead>
<tr>
<th></th>
<th>This work</th>
<th>[1]</th>
<th>[2]</th>
<th>[3]</th>
<th>[4]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tech</td>
<td>0.18</td>
<td>1.5</td>
<td>0.18</td>
<td>0.35</td>
<td>0.18</td>
</tr>
<tr>
<td>Supply (V)</td>
<td>1.2</td>
<td>5</td>
<td>0.5</td>
<td>2.5</td>
<td>1.8</td>
</tr>
<tr>
<td>fs (Hz)</td>
<td>128,16,13,4</td>
<td>100</td>
<td>32k</td>
<td>100</td>
<td>165</td>
</tr>
<tr>
<td>I_{dc} cancel.</td>
<td>&lt; 10μA</td>
<td>-</td>
<td>&lt;4μA</td>
<td>56.3μA</td>
<td>100μA</td>
</tr>
<tr>
<td>Noise (RTI)</td>
<td>486pA_{rms}</td>
<td>-</td>
<td>-</td>
<td>2.2nA_{rms}</td>
<td>600pA_{rms}</td>
</tr>
<tr>
<td>Noise BW</td>
<td>10 Hz</td>
<td>-</td>
<td>-</td>
<td>6 Hz</td>
<td>10 Hz</td>
</tr>
<tr>
<td>LED control</td>
<td>✓</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>✓</td>
</tr>
<tr>
<td>Feature Extr.</td>
<td>HR/HRV</td>
<td>SpO₂</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Readout (μW)</td>
<td>172</td>
<td>400</td>
<td>4</td>
<td>600</td>
<td>216</td>
</tr>
<tr>
<td>LED driver (μW)</td>
<td>1200-43 (1x-30x CR)</td>
<td>4400</td>
<td>NA</td>
<td>-</td>
<td>1125-120</td>
</tr>
</tbody>
</table>

[1] Tavakoli, TBCAS10  
[3] Wong, TBCAS08  
PPG ASIC HET Integration

Black: ASIC                       Grey: External
Ultra-flexible and organic PPG/PulseOx

State of the art

- Few publications so far and all recent
  - 2010, Chuo et al. IEEE Sensors Conference
  - 2014, Lochner et al. Nature Communications
  - 2014, Bansal et al. Advanced Materials
  - 2016, Yokota et al. Scientific Advances
  - 2017 Han et al. Advanced Materials
  - 2017 Kramer et al. Military Medicine

- All proof of concept demonstration
- Poor wearability
- No power reduction emphasis
Ultra-flexible, strongly tissue coupled PPG/pulse oximeter sensing

- **Technical barrier:**
  - Manufacturing of stable flexible optical devices,
  - Efficient coupling with the tissue,
  - Absence of wearable form factor flexible embedded systems

- **Solution:**
  - Polymer OLED/OPD and thinned inorganic LED/PMT
  - Surface patterning for improved light coupling to the tissue
  - Stretchable and flexible substrates for circuit board fabrication

- **Current status:**
  - Industry collaboration for polymer organic devices
  - Moth eye structure fabrication, in progress.
  - Stretchable and flexible PCB fabrication, in progress.
Year 6 roadmap and progress

Integration of the ultra low power PPG ASIC into HET

Design and manufacturing of an ultra-low power organic photodevice based wearable pulse oximeter system
QUESTIONS....
Liquid Metal for Wearable Electronics

January 18, 2018
Michael Dickey (NC State)
Taylor Neumann, Yasaman Sargolzaeiaval, Dishit Parekh, Francisco Saurez, Mehmet Ozturk
Flexible, Soft, Stretchable Electronics
Liquids: Inherently Soft and Stretchable

Liquid Metal
Eutectic Gallium Indium (EGaIn)

Gallium

Melting point: 30 °C

Indium

157 °C

Liquid

16 °C
~3 nm Surface Oxide Dominates Behavior

Oxide Skin:
- 3 nm thick (TEM)
- “Passivating”
- Oxides of gallium (Auger)
Microfluidics to Pattern Metal
Self-healing
Ultra-stretchable Wires

“The two most important parameters for stretchable interconnects are high electrical conductance and large critical strain at which conduction is lost.” Wagner & Bauer, MRS Bulletin, 2012.


Shu Zhu et. al Adv Fun. Mat. 2013
Stretchable Sensors: Touch

Harvesting Heat from the Body

Flexible thermoelectric generators (TEGs):
- Conformal to the body
  - Better contact with the skin
  - Comfortable

w/ Mehmet Ozturk
Thermoelectrics with Liquid Metal Interconnects

Conventional TEG

Substrates eliminated

PDMS Encapsulation

Liquid Metal Interconnects
Mechanical Testing

Suarez et al., Flexible thermoelectric generator using bulk legs and liquid metal interconnects for wearable electronics, Applied Energy 2017
Improved Performance

- Ya Yang (2012)
- Kitoigava (2005)
- SJ. Kim (2014)
- F. Suarez (2016)
- Our work

Flexible TEGs

Power (µW/cm²)
Soft Electrodes

(a) Hydrogel

EGaIn

PDMS

(b) PDMS

EGaIn

Hydrogel

Graphs showing comparison between Commercial, PBS Gel, and Bilayer Gel over time.
Conclusions

- Oxide enabled patterning
  - Ultra-stretchable wires, 3D printing
- Improved wearables
  - Stretchable TEG, Soft EKG
Non-Invasive, Long-Term Sweat Sampling Devices by Biomimetic Osmotic Principles

Tamoghna Saha, Tim Shay, Michael D. Dickey, Orlin D. Velev
Benchmarks in Academia

Sweat sensing devices are a topic of fascinating research, but face a number of challenges…
Sweat Sequestering and Sensing Challenges

- Current devices have difficulties collecting sweat during low sweat periods and managing the fluid after it has been sensed.

- Real-time sensing of many common analytes in sweat is not always usable or feasible.

<table>
<thead>
<tr>
<th>Sweat (mM)</th>
<th>Bioanalyte</th>
<th>Indicator For</th>
<th>Blood (mM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.02 - 0.36</td>
<td>Glucose</td>
<td>Diabetes</td>
<td>4 - 12</td>
</tr>
<tr>
<td>10 - 100</td>
<td>Sodium (Na⁺)</td>
<td>Hydration</td>
<td>135 - 150</td>
</tr>
<tr>
<td>10 - 100</td>
<td>Chloride (Cl⁻)</td>
<td>Hydration</td>
<td>96 - 106</td>
</tr>
<tr>
<td>4 - 24</td>
<td>Potassium (K⁺)</td>
<td>Hydration</td>
<td>5 - 6</td>
</tr>
<tr>
<td>0.5 - 8</td>
<td>Ammonium (NH₄⁺)</td>
<td>Liver Failure</td>
<td>20 - 50</td>
</tr>
<tr>
<td>2.5 - 22.5</td>
<td>Ethanol</td>
<td>Alcohol Use</td>
<td>2.25 - 22.5</td>
</tr>
<tr>
<td>2.21 - 38.6 x 10⁻⁵</td>
<td>Cortisol</td>
<td>Stress</td>
<td>12.4 - 4 x 10⁻⁵</td>
</tr>
<tr>
<td>5 - 60</td>
<td>Lactate</td>
<td>Exertion</td>
<td>1 - 7</td>
</tr>
</tbody>
</table>

Sonner et al. Biomicrofluidics 2015
ASSIST Hydrogel and Osmotic Pressure Innovation

Osmotic pressure is based on differences in concentration \( \Pi = iRT\Delta C \)

- Osmotic pressure gradients are the major mechanism Nature uses to move fluids, including sweat

Osmotic Sweat Intake

- We have pioneered this principle to draw fluid through the skin
- Patent-pending hydrogel based devices
- Simple, reliable, long-term operation

Sonner et al. Biomicrofluidics 2015
Goal: Utilize the osmotic properties of hydrogels to passively pump sweat from the body through a flexible microfluidic network where biochemical sensors can be embedded to promote continual non-invasive biochemical sensing in a wearable platform.
Example of osmotically pumped sensing

Can we perform biochemical sensing on this solution that accumulates at the outlet?

Successfully monitored glucose levels through passive non-invasive pumping

Shay, Dickey and Velev, *Lab Chip*, 17, 710 (2017)
New Paper-Hydrogel Concept

Concept 1.0

Concept 2.0

Combine paper microfluidics and hydrogels for new platform

- Paper naturally wicks sweat under high sweat rates
- Hydrogel provides pumping under low sweat rates
Evaporation Pumping with Paper Microfluidics

**Primming Phase**
- Less than 1 hour

**Continual Long-term Pumping**
- 0 - 10 days

- **Evaporation Pad**
- **Encased Paper Channel**
- **Electrodes**
- **Sampling Fluid**

**Can be Combined with Electrical Impedance Sensing**

Can be combined with electrical impedance sensing

Demonstrated sensing on both a colorimetric and an impedance based electrical systems - further work will be in collaboration with Michael Daniele and Jason Strohmaier
Evaporation Pumping with Paper Microfluidics 2

The devices have large capacity and can operate for days or weeks.
Key Technical Proof of Operation

- IRB testing of osmotic dye retrieval from human skin

- Proved that as expected osmotic pressure effects are critical for device operation
Another promising application of the osmotic pumping principle - microneedles

- The microfluidic-osmotic principle provides a powerful platform for physiological pumping
- This principle may also be used as means of withdrawal of ISF from microneedle devices
- Could be interfaced with Prof. Daniele’s microneedle patches
- Looking for industrial partners who may use the osmotic ISF withdrawal from microneedle patches

The ISF collected by the microneedles is held there by capillarity and has to be pumped out.
Device 2.1 design

1. Hydrogel osmotically pumps fluid from the skin to the device
2. Pumped fluid is wicked through the paper microfluidic network
3. Evaporation occurs on the back end to continually drive fluid flow
4. Porous superhydrophobic layer protects the evaporation patch

✓ This device will form the basis of the future wearable skin patches for drug monitoring
Supplementary device-enhancing technology: Superhydrophobic protective coatings

- Velev group has invented highly efficient materials for resilient water-repelling coatings
- Based on new types of dendrimeric polymer particles
- Could be made and used in large quantities and inexpensively
- Ideal for protection of gas sensors or wearable devices
**Device 2.1 as a wearable patch**

**Accumulative Testing:** Measure total amount of analyte collected in evaporation pad over long collection time

**Long-time Trend Recording:** Measure variation in analyte concentration based on profile formed on evaporation pad
Future Wearable Devices Concept

We foresee use in wearable patches that could sense drugs and deliver by feedback
A Capacitive Micromachined Ultrasonic Transducer (CMUT) Array As a Low-Power Multi-Channel Volatile Organic Compound (VOC) Sensor and More…

Ömer Oralkan
Department of Electrical and Computer Engineering
North Carolina State University

Other contributors: X. Zhang, O. J. Adelegan, X. Wu
Volatile organic compounds are major pollutants in indoor and outdoor environments as well as in industrial settings.

- Personalized exposure monitoring is important to link the environment to the physiological state.

- In industrial settings the distance between the monitoring sensor and the source of the VOC could cause measurement errors in total exposure.

http://www.theozonehole.com/badozone.htm
Commercially available VOC sensors are not suitable for use in wearable platforms

- Usually offered as total VOC sensors, not specific to different types of VOCs.
- Traditional MOx type sensors require heating.
- Power consumption is in the tens of mW range, which is not suitable for self-powered wearable platforms.
<table>
<thead>
<tr>
<th>Product</th>
<th>Target gases</th>
<th>Sensing principle</th>
<th>Sensing range</th>
<th>Power consumption</th>
<th>Operating temperature &amp; response time</th>
<th>Datasheet &amp; Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figaro TGS-2602</td>
<td>Air contaminants (VOCs, ammonia, H₂S, etc.)</td>
<td>MOS type</td>
<td>1 ~ 30ppm of EtOH</td>
<td>280 mW (typical)</td>
<td>Room temperature</td>
<td><a href="http://www.figaro.co.jp/en/product/docs/tgs2602_product%20information%28en%29_rev03.pdf">http://www.figaro.co.jp/en/product/docs/tgs2602_product%20information%28en%29_rev03.pdf</a></td>
</tr>
<tr>
<td>AS-MLV-P2</td>
<td>VOCs and CO</td>
<td>MOS type</td>
<td>Low ppm range</td>
<td>34 mW</td>
<td>300°C</td>
<td><a href="https://ams.com/kor/content/download/686543/1787717/file/AS-MLV-P2_Datasheet_EN_v1.pdf">https://ams.com/kor/content/download/686543/1787717/file/AS-MLV-P2_Datasheet_EN_v1.pdf</a></td>
</tr>
<tr>
<td>iAQ-core C 70-0100</td>
<td>VOCs and CO₂</td>
<td>MOS type</td>
<td>450 – 2000 ppm CO₂ equivalents</td>
<td>66 mW (maximum in continuous mode)</td>
<td>0°C to 50°C First functional reading after start up = 5 minutes</td>
<td><a href="">file:///C:/Users/mmahmud/Downloads/iAQ-core_Datasheet_EN_v1.pdf</a> $36/piece (min. 10 pcs)</td>
</tr>
</tbody>
</table>
Mechanically resonant sensors with polymer functionalization layers present an alternative way of sensing

- Quartz Crystal Microbalance (QCM)
- Surface Acoustic Wave (SAW)
- Lamb Wave Resonators
- Cantilevers
- Film Bulk Acoustic Resonator (FBAR)

- Capacitive Micromachined Ultrasonic Transducer (CMUT)
The polymer functionalization layer converts the mass sensor to a gas sensor

- Mass loading effect decreases resonant frequency.
- Higher frequency, lower unit membrane mass and lower frequency noise are required for better mass resolution.
- Higher power will be consumed by the electrical circuits at higher frequencies.
- Potential for attogram sensitivity and large dynamic range.

\[
\frac{\Delta f}{f} \propto \frac{\Delta m}{m}
\]
The Capacitive Micromachined Ultrasonic Transducer (CMUT) offers advantages for resonant chemical sensing.

- **Target analyte**: VOCs
- **Basic CMUT structure**
  - Single-crystal silicon thin plate
  - Silicon nitride insulation layer
  - Vacuum gap
  - Chromium/gold bottom electrode
  - Glass substrate

- **Advantages**
  - **Vacuum-sealed cavity exhibits a higher quality factor**
  - **Cells connected in parallel ensures robust operation**
  - **Multi-channel arrays with elements functionalized with various polymers enhance**

- **Surface functionalization**
- **Mechanical resonator**
- **Electrical oscillator**
- **Startup circuit**
- **Main processor**
- **Frequency counter**
- **Frequency shift (kHz)**
  - 10 ppm
  - 12 ppm
  - 14 ppm
  - 16 ppm
  - 18 ppm
  - 20 ppm

- **Digital data**
  - **Time (mins)**
  - clean air
toluene clean air
Ppb-level detection of volatile organic compounds (VOCs) can be achieved at lower frequencies with low power.

Previous CMUT-based resonant chemical sensors for defense applications:

CMUT resonant sensors for DMMP detection [1]
- High resonant frequency (47.7 MHz)
- High volume sensitivity of 34.5 ppt/Hz
- High power consumption of 80 mW


Current focus: Low-power wearable sensors for environmental monitoring:

<table>
<thead>
<tr>
<th>Target Analyte</th>
<th>OSHA PEL-TWA</th>
<th>OSHA PEL- STEL</th>
<th>NIOSH REL-TWA</th>
<th>NIOSH IDLH</th>
<th>Range for Target Detection Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toluene</td>
<td>200 ppm</td>
<td>N/A</td>
<td>100 ppm</td>
<td>500 ppm</td>
<td>2-20 ppm</td>
</tr>
<tr>
<td>Formaldehyde</td>
<td>750 ppb</td>
<td>2 ppm</td>
<td>16 ppb</td>
<td>20 ppm</td>
<td>7.5-75 ppb</td>
</tr>
<tr>
<td>Xylene</td>
<td>100 ppm</td>
<td>N/A</td>
<td>100 ppm</td>
<td>900 ppm</td>
<td>1-10 ppm</td>
</tr>
<tr>
<td>Benzene</td>
<td>1 ppm</td>
<td>5 ppm</td>
<td>0.1 ppm</td>
<td>500 ppm</td>
<td>10-100 ppb</td>
</tr>
</tbody>
</table>

- High-ppb-to-ppm-level detection is adequate.
- Sensitivity can be traded off for the low power requirement.
We developed a novel fabrication process to make CMUTs with three lithographic steps.

RMS surface roughness:
- 2 nm on the metal surface in the cavity after lift-off
- 0.7 nm on the post region

Q-factor in the range of hundreds.

We developed a novel fabrication process to make CMUTs with three lithographic steps:

(a) Pattern cavities  (b) Etch glass.  (c) Form bottom metal

(d) Anodic bonding  (e) Plate release  (f) Pattern/etch plate

(g) Seal in vacuum  (h) Etch sealing layer  (i) Deposit top metal

VOC sensing: We also design custom low-power (10 µW) frontend integrated circuits for complete system implementation with a digital output.
A single CMUT was used for proof of principle.

The surface was functionalized with a peptide ligand selective to IgG.

FITC tagged IgG that had been bound to the surface was fluorescently visible after incubation and washing.

0.44 ag/µm² mass resolution was achieved.

Frequency shift measured after each step. Frequency measured in air after drying.

**Experimental step** | **Frequency shift (kHz)** | **Added mass (fg/µm²)**
--- | --- | ---
Thiol-PEG | 9.50 | 4.14
Thiol-PEG-Peptide | 28.03 | 12.29
Thiol-PEG-Peptide-IgG | 31.57 | 13.86

**Biosensing:** We also used the gravimetric sensors for sensing IgG using peptide ligand functionalization.

By replacing metal bottom electrodes with ITO we realized transparent versions of these transducers.

Improved transparency presents opportunities for photoacoustic imaging

Transmission through an element

Wavelength range used in PA imaging
We demonstrated photoacoustic imaging using direct transmission through the transducer element.

By further improving the optical transparency we enable display-embedded human-machine interfaces

A single 50-kHz transducer on a 100-mm wafer

60-80% Transmission in the visible wavelength range

26 nm/V displacement at 50 kHz when biased at 70-V DC

Possible interfaces:
- Directional sound source (parametric array)
- Gesture recognition
- Fingerprint scanner

With an improved device structure we have not only reduced charging in sensors but also enabled a new operating mode for imaging.

Conclusion

- We have developed a highly integrated low-power multi-channel sensor system for selectively sensing VOCs.
- We have implemented the same approach for biosensing using peptide ligand functionalization.
- The same basic technology enabled novel transducers for imaging and human-machine interfaces.
Development of Miniaturized Hybrid Capacitors
(Thrust #1)

PI – Chunlei (Peggy) Wang
Graduate Students – Ebenezer Adelowo, Richa Agrawal, Amin Rabiei, Vadym Drozd
# Project Goals

**Ultimate Goal:** To develop miniaturized hybrid capacitor, which combines double layer and reversible redox reaction mechanisms at electrode level. Such a capacitor will benefit from the combination of both mechanisms to deliver high energy density, high power density, fast charge capability and long cycle-life.

<table>
<thead>
<tr>
<th>Task</th>
<th>Goal</th>
<th>Timeline</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td><strong>Aqueous on-chip hybrid microsupercapacitors</strong>&lt;br&gt;Continuing the efforts manganese oxide and nanostructured carbon based on-chip hybrid interdigitated microsupercapacitors.</td>
<td>Summer 2017</td>
</tr>
<tr>
<td>2.</td>
<td><strong>Scale up Solid state LIHS GLA-I</strong>&lt;br&gt;Identifying and optimizing Li₄Ti₅O₁₂-based battery-type anode and graphene-carbon nanotube (CNT) cathode composition with gel polymer electrolyte (GPE) in solid state LIHS system packaged in CR 2032 type coin cells.</td>
<td>Fall 2017-Spring 2018</td>
</tr>
<tr>
<td>3.</td>
<td><strong>Scale up Solid state LIHS GLA-II</strong>&lt;br&gt;Constructing and evaluating solid state LIHS using optimized electrode materials with Li₂S·P₂S₅ glass-ceramic electrolyte packaged CR 2032 type coin cells.</td>
<td>Spring-Summer 2018</td>
</tr>
<tr>
<td>4.</td>
<td><strong>Miniaturization of solid state LIHS</strong>&lt;br&gt;Development of miniature LIHS with Li₄Ti₅O₁₂-based battery-type anode and graphene-carbon nanotube (CNT) materials with solid electrolyte. Target size -5mm X 5mm X 200 μm packaged pouch cell.</td>
<td>Summer 2018-Fall 2018</td>
</tr>
<tr>
<td>5.</td>
<td><strong>Further Miniaturization of solid state LIHS</strong>&lt;br&gt;Continuing the development of miniature solid state LIHS with Li₄Ti₅O₁₂-based battery-type anode and graphene-carbon nanotube (CNT) materials with solid electrolyte. Target size -3mm X 3mm X 200 μm and -1mm X 1mm X 200 μm.</td>
<td>Fall 2018-Spring 2019</td>
</tr>
<tr>
<td>6.</td>
<td><strong>Packaged miniature LIHS deliverables for tested integration</strong>&lt;br&gt;Miniature solid state LIHS will be delivered to power the ASSIST testbed.</td>
<td>Summer 2019</td>
</tr>
</tbody>
</table>
Hybrid electrochemical capacitors

- The global market for supercapacitors: $1.21 billion in 2014, $7.37 billion by 2023

- Applications: Memory back-up, EV, Power quality, Portable power supplies...

- Hybrid capacitors: asymmetric capacitors, hybrid composites, battery type hybrid capacitors (such as LIC)

- The advantages of hybridization in electrochemical energy storage devices:
  - Higher energy density than ECs
  - Higher power density than batteries
  - High cycle longevity

- LIC Materials:
  - 1st LIC, by Amatucci in 2001, LTO / AC
  - Commercial LIC: pre-doped graphite / AC

Desired energy and power
The Need for Miniaturized Energy Storage Units

Small-scale Electronic Devices
- Cardiac pacemakers
- Hearing aids
- Smart cards
- Personal gas monitors
- MEMS devices
- Embedded monitors
- Remote sensors

Typically for MSCs
- Footprint (mm to cm range)
- Thin film electrodes with thickness less than 10 μm or
- Arrays of microelectrodes with micron-scale sizes in at least two dimensions, or
- Devices with three-dimensional (3D) architectures of nanoscale building blocks.

Challenges?
- Shrinking the size of the MSC decreases active material loading and eventual decrease in capacitance
- Currently existing EES components still much larger than IC components
- How to effectively enhance the performance of the MSC in the limited footprint?
Device Development: Platforms + Materials

Carbon Microelectromechanical Systems (C-MEMS)

(a) Spin-coating photoresist
   → SU-8 photoresist
   → Substrate

(b) UV exposure
   → Lithographer
   → Mask

(c) Developing
   → SU-8 post

(d) Pyrolysis
   → Carbon Post

Electrodeposition techniques

Electrostatic Spray Deposition (ESD)

Electrophoretic Deposition

Electrochemical Deposition
Hausmannite $\text{Mn}_3\text{O}_4$

- $\sim 595 \text{ cm}^{-1}$ - tetrahedral
- $\sim 510 \text{ cm}^{-1}$ - octahedral distortion vibrations of Mn-O

With the addition of CNTs to the $\text{MnO}_x$, the absorption peaks in the low-mid frequency region (700-1700 cm$^{-1}$) start becoming more pronounced.
Empirical Electrochemical Performance Optimization

Microstructure

- 3D reticular network
- "Layered" platelet-like microstructure.
- HRTEM analysis shows a combination of hausmannite and birnessite phases.

ESD based MnO$_x$-CNT

Mn$_3$O$_4$ → MnO$_2$

55 mF cm$^{-2}$
0.51 mWh cm$^{-3}$
28.3 mW cm$^{-3}$
Empirical Electrochemical Performance Optimization

**MnO$_x$ based half-cell**

Table 1: $R_s$ and $R_{ct}$ values of the pristine MnO$_x$, MnO$_x$-CNT 9-1 and MnO$_x$-CNT 8-2 electrodes

<table>
<thead>
<tr>
<th>Electrode</th>
<th>$R_s$ (Ω)</th>
<th>$R_{ct}$ (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MnO$_x$</td>
<td>9.57</td>
<td>681.00</td>
</tr>
<tr>
<td>MnO$_x$-CNT 9-1</td>
<td>4.76</td>
<td>282.00</td>
</tr>
<tr>
<td>MnO$_x$-CNT 8-2</td>
<td>2.31</td>
<td>185.70</td>
</tr>
</tbody>
</table>

✓ The MnO$_x$-CNT 9-1 composition exhibited superior electrochemical performance as compared to both the pristine MnO$_x$ and the MnO$_x$-CNT 8-2 composite films.

✓ The MnO$_x$-CNT 9-1 electrodes exhibited a high specific capacitance of 281 Fg$^{-1}$ for a current rate of 0.2Ag$^{-1}$ and were able to retain 87.4% of the maximal capacitance after 1000 cycles.
Full-cell characterization

- Largely rectangular shape of the CV curves indicates largely capacitive charge storage
- Triangular sloping-desloping curves with some curvature observed, which can be attributed to the hybrid charge storage characteristics
- Symmetric AC//AC system maintains the best capacitive retention (~100%); hybrid cap (~76%); symmetric MnO$_x$-CNT 9-1 cap (~56%)
- Maximal energy density deliverable by the system (30.3 Whkg$^{-1}$); ED does not decay fast as the PD progresses
**Empirical Electrochemical Performance Optimization**

Electrochemical characteristics of the symmetric AC//AC system, symmetric MnO$_x$-CNT 9-1//MnO$_x$-CNT 9-1 system, and the optimized asymmetric MnO$_x$-CNT 9-1//AC system

<table>
<thead>
<tr>
<th>System</th>
<th>Capacitive retention</th>
<th>Cell Voltage</th>
<th>Cell Capacitance (Fg$^{-1}$)</th>
<th>ED (Whkg$^{-1}$) (from Ragone Chart)</th>
<th>PD (Wkg$^{-1}$) (from iR calculations)</th>
<th>PD_{max} (Wkg$^{-1}$) (from iR calculations)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Symmetric AC//AC</td>
<td>~100% after 500 cycles</td>
<td>1.2V</td>
<td>28</td>
<td>5.6</td>
<td>600</td>
<td>888</td>
</tr>
<tr>
<td>Symmetric MnO$_x$-CNT 9-1//MnO$_x$-CNT 9-1</td>
<td>56.4% after 500 cycles</td>
<td>0.8V</td>
<td>49.9</td>
<td>4.4</td>
<td>800</td>
<td>1454</td>
</tr>
<tr>
<td>Asymmetric MnO$_x$-CNT 9-1//AC (MR: 1:2.6)</td>
<td>76% after 500 cycles</td>
<td>2V</td>
<td>54.5</td>
<td>30.3</td>
<td>2000</td>
<td>4000</td>
</tr>
</tbody>
</table>

✓ Maximal energy density of 30.3 Whkg$^{-1}$ achieved, the improvement energy-power trade-off is ascribed to the large 2V potential window and high capacitance from the MnO$_x$-CNT 9-1 electrode.
Miniaturized Hybrid Device

reduced Graphene Oxide (rGO)/Manganese Oxide (MnO$_2$)
Miniaturized Hybrid Device

Microstructural Characterization

a) MnO
b) rGO cross section
c) rGO top-view

d) MnO$_x$ 0.6 Ccm$^2$
e) MnO$_x$ 0.9 Ccm$^2$
f) MnO$_x$ 1.2 Ccm$^2$

g) MnO$_x$ 0.6 Ccm$^2$
h) MnO$_x$ 0.9 Ccm$^2$
i) MnO$_x$ 1.2 Ccm$^2$
Miniaturized Hybrid Device
rGO based symmetric micro-device

-a) Primarily rectangular shape of the CV curves indicates surface dominated charge storage

-b) Typical triangular shape of the galvanostatic charge-discharge curves

-c) The discharge areal capacitances were estimated as ~252, 223, and 172 µFcm⁻² at current densities of 0.32, 0.64, and 1.28 mAcm⁻², respectively

-d) Very low charge transfer resistance

-e) Good cycling stability; ~97% retention after 100 cycles
Miniaturized Hybrid Device
MnO\textsubscript{x} based symmetric micro-device

- Typical capacitor shape observed in the CV curves
- Typical triangular shape with curvature
- The discharge areal capacitances were estimated as 147, 96, 64 \( \mu \)Fcm\(^{-2}\) at current densities of 0.16, 0.32, 0.64 mAcm\(^{-2}\), respectively
- Low charge transfer resistance
- Low capacitive retention (~58% after 1000 cycles)

**Electrolyte:** 1M Na\textsubscript{2}SO\textsubscript{4}
Electrochemical Characterization

rGO//MnO$_x$ hybrid micro-device

- Composite charge storage characteristics evident from the CV curves
- Superior current response as compared to the two symmetric systems
- Composite charge storage evident in GCD curves
- 1.63, 1.59, 1.29, and 1.2 mF cm$^{-2}$ at current densities of 0.32, 0.64, and 1.28, and 2.56 mA cm$^{-2}$, respectively
- Higher resistance than the symmetric systems
- Intermediate cycle life (~85% capacitance retention)
The asymmetric microsupercapacitor with the MnOx film deposited at a charge of 0.9 C cm\(^{-2}\) displayed the optimal energy-power trade-off.

The rGO//MnOx 0.9C microsupercapacitor exhibited a high stack energy density of 1.02 mWh cm\(^{-3}\) and a maximal power density of 3.44 W cm\(^{-3}\).
Gel polymer electrolyte (GPE) for LIC

Advantages of GPE:
- No risk of electrolyte leakage
- Non flammability
- Wide electrochemical window

Application of the GPE:
Electrode material: Li₄Ti₅O₁₂ (half cell versus lithium)

Voltage range of the GPE

Structure of the GPE components

Material synthesis and characterization:
Precursors: Lithium acetate dihydrate, Titanium (IV) butoxide.
Solvents: DI water (5 ml), Methanol (30 ml)

Electrode preparation (ESD) → Half cell assembly with GPE → Electrochemical evaluation
**Gel polymer electrolyte (GPE) for LIC**

**Material Characterization**
- SEM image show agglomeration of nanoparticles.
- The XRD data matched with standard data confirms the nanoparticles as pure Li$_4$Ti$_5$O$_{12}$.
- Sharp peaks indicate high degree of crystallinity.

**Electrochemical Test**
- Discharge capacity of 149 mAh/g at C/10 current density (85% of theoretical capacity of 175 mAh/g).
- Good rate capability.
Three different manganese oxide compositions: i) pristine (MnOx), ii) with 10% carbon nanotube additive (MnOx-CNT9-1), and iii) 20% CNT additive (MnOx-CNT8-2) were synthesized using electrostatic spray deposition and investigated in aqueous media. The MnOx-CNT9-1 composition exhibited superior electrochemical performance as compared to both the pristine MnOx and the MnOx-CNT8-2 composite films. The -CNT9-1 electrodes exhibited a high specific capacitance of 281 F g\(^{-1}\) for a current rate of 0.2 A g\(^{-1}\) and were able to retain 87.4% of the maximal capacitance after 1000 cycles. Asymmetric capacitors were constructed using MnOx-CNT9-1 electrodes and slurry casted AC electrodes in different mass ratios; capacitor with mass ratio 1:2.6, with the latter corresponding to the mass of AC, exhibited the best electrochemical characteristics. Maximal energy density of 30.3 Wh kg\(^{-1}\) achieved, the improvement energy-power trade-off is ascribed to the large 2V potential window and high capacitance from the MnOx-CNT9-1 electrode.

Interdigitated microsupercapacitors were fabricated using photolithography, lift-off and electrodeposition methods. Symmetric MnO\(_x\)//MnO\(_x\), rGO//rGO as well as asymmetric hybrid rGO//MnO\(_x\) microsupercapacitors with three different MnO\(_x\) thicknesses were constructed and evaluated. The asymmetric microsupercapacitor with the MnO\(_x\) film deposited at a charge of 0.9 C cm\(^{-2}\) displayed the optimal energy-power trade-off much superior to that of both the symmetric and well as the other asymmetric configurations. The rGO//MnO\(_x\) 0.9C microsupercapacitor exhibited a high stack energy density of 1.02 mWh cm\(^{-3}\) and a maximal power density of 3.44 W cm\(^{-3}\) both of which are comparable with thin film batteries and commercial supercapacitors in terms of volumetric energy and power densities, respectively.

Development of scale-up hybrid capacitor system with solid/semi solid electrolytes and different electrode configuration is ongoing.
ASSIST Center: Testbeds

Industry Advisory Board Meeting

Dr. Alper Bozkurt (NCSU)
HET Leader

Jason Strohmaier (NCSU)
CSE

John Lach (UVA)
SAP Leader
Engineered systems demonstrates the two compelling visions of ASSIST

**Self-powered Adaptive Platform (SAP):**
Ultra-low power wearable technologies self-powered by the energy harvested from the body

**Health and Exposure Tracker (HET):**
Correlated sensing of health and exposure to provide feedback for actionable decisions

**The goal of today’s presentation**

- To provide the latest update with the construction and deployment of the engineered systems
- To inform about how use cases drive Center Testbed definitions and requirements
- To demonstrate the shaping of the testbeds through the three-pronged interaction between
  - ASSIST Center Testbed project leads
  - ASSIST and/or Center-associated medical leads for requirements
  - Industry partnerships for needs, IP, joint projects, commercialization
**SAP 1.0**

**Use Case: Vigilant Arrhythmia**
- hr/hrv sensing via ECG
- motion tracking
- constant communication
- long-term wearable

**Energy Harvesting: Heat**

**Energy Storage**

**Ultra Low Power Radios**

**Textiles/Wearability**

**ULP Electronics**

**Flexible Antenna**
**Use Case: Asthma**
- hr/hrv/ptt via ECG/PPG
- movement and air exposure tracking
- correlation between health, environment and behavior

**Data Activity Identification**

**Data Algorithms**

**Low Power Ozone**

**Low Power VOC**

**Low power PPG**
ASSIST Use Case & Specification Process

1. Get customer input through value proposition canvas
2. Translate customer needs to technical requirements for Testbeds
3. Adjust requirements based on barriers. Use barriers to define future research
4. Drive requirements through Testbeds to researchers
5. Integrate components into HET and SAP
6. Test/Refine Performance against requirements
7. Deliver prototype to customers for field studies
8. Scale up/translate or refine customer needs if necessary
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Translating Customer Needs via Research, Medical, Industry Leadership

**GEN 1**

**Asthma**
- Center Leads: Ajay Bedi, NC State, ECE; Dr. David Reden, UNC, Pediatrics
- Medical Advisors: Dr. David Reden, UNC, Pediatrics; Dr. Michelle Hernandez, UNC, Pediatrics
- Industry Partners: RTI International

**Arrhythmia**
- Center Leads: John Cao, UVA, ECE
- Medical Advisors: Dr. Randall Martin, UVA, Biomedical
- Industry Partners: S & S

**GEN 2**

**Pre-Diabetes**
- Center Leads: Ajay Bedi, NC State, ECE; Michael Strain, NC State, Biomedical
- Medical Advisors: Dr. John Buse, UNC, Endocrinology
- Industry Partners: profusa

**Wound Care**
- Center Leads: Steven Ehasazi, Florida International, ECE
- Medical Advisors: Dr. Robert Kinner, M.D., Seminole Medical, Dr. Paul C. Chou, M.D., College of Medicine
- Industry Partners: Merck

**GEN 3**

**Medication Detection**
- Center Leads: Ajay Bedi, NC State, ECE; Michael Currey, NC State, Biomedical
- Medical Advisors: Dr. Dana Carpenter, UNC, Pharmacy
- Industry Partners: muraTec, Noven, novEN, Eastman

**Chief Systems Engineer**
### Example: SAP Gen 1 System Specifications

<table>
<thead>
<tr>
<th>Testbed Embodiment</th>
<th>ECG Shirt</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inputs</strong></td>
<td>ECG Electrodes</td>
</tr>
<tr>
<td></td>
<td>Accelerometer</td>
</tr>
<tr>
<td></td>
<td>Thermoelectric harvesters</td>
</tr>
<tr>
<td></td>
<td>Piezoelectric harvesters</td>
</tr>
<tr>
<td><strong>Outputs</strong></td>
<td>ECG waveform</td>
</tr>
<tr>
<td></td>
<td>Heart rate</td>
</tr>
<tr>
<td></td>
<td>Heart rate variability</td>
</tr>
<tr>
<td></td>
<td>Health warnings</td>
</tr>
<tr>
<td><strong>Operational Lifetime</strong></td>
<td>Unit: &gt; One year</td>
</tr>
<tr>
<td></td>
<td>ECG Shirt: &gt; Fifty washes</td>
</tr>
<tr>
<td><strong>Biocompatibility</strong></td>
<td>Continuous use for operational lifetime w/out skin irritation, toxicity</td>
</tr>
<tr>
<td><strong>User Interface</strong></td>
<td>Smartphone-based aggregator</td>
</tr>
<tr>
<td></td>
<td>Physician/patient portal</td>
</tr>
<tr>
<td><strong>User Feedback</strong></td>
<td>Heart health and activity-monitoring feedback</td>
</tr>
<tr>
<td><strong>System Power Source</strong></td>
<td>Thermoelectrics, Piezoelectrics, Supercapacitor</td>
</tr>
<tr>
<td>Testbed Embodiment</td>
<td>ECG Shirt</td>
</tr>
<tr>
<td>--------------------------</td>
<td>---------------------------------------------------------------------------</td>
</tr>
<tr>
<td>ECG Complex</td>
<td>RA (right upper chest) / LA (left upper chest) / LL (left lower chest)</td>
</tr>
<tr>
<td>ECG Measurement Range</td>
<td>30-200 beats per minute</td>
</tr>
<tr>
<td>ECG Measurement Frequency</td>
<td>50Hz</td>
</tr>
<tr>
<td>Acc Measurement Range</td>
<td>+/-2g</td>
</tr>
<tr>
<td>Acc Measurement Frequency</td>
<td>200Hz</td>
</tr>
<tr>
<td>TEG Energy Density</td>
<td>&gt; 20µW/cm² at room temperature, no airflow</td>
</tr>
<tr>
<td></td>
<td>&gt; 100µW/cm² at room temperature, 1m/s airflow</td>
</tr>
<tr>
<td>Boost Converter Type</td>
<td>Unipolar</td>
</tr>
<tr>
<td>Boost Converter Input Voltage</td>
<td>50mV - 1V</td>
</tr>
<tr>
<td>Supercapacitor Capacity</td>
<td>1 Farad</td>
</tr>
<tr>
<td>Communication Frequency</td>
<td>2.44 GHz / ISM Band</td>
</tr>
<tr>
<td>System Operating Range</td>
<td>&gt;1 meter</td>
</tr>
<tr>
<td>Total System Power</td>
<td>&lt; 100µW</td>
</tr>
</tbody>
</table>
ASSIST Use Case & Specification Process

1. Get customer input through value proposition canvas

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Example: SAP Gen 1 (Vigilant aFib Detection)
Example: SAP Gen 1 (Vigilant aFib Detection)

“Knee” at 50Hz consistent with minimum R-spike width of ~80ms (i.e., at least 4 samples per spike at 50Hz)

COTS average power consumption for vigilant sampling
- 750uW @ 50Hz vs 3500uW @ 250Hz

SAP 1.0 average power consumption for vigilant sampling
- 12uW @ 50Hz vs 16uW @ 250Hz
1. Get customer input through value proposition canvas
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System requirements
- high energy harvesting
- high capacity storage
- ultra-low power consumption
- Integrated ECG electrode
- always on ECG & motion
- industry standard wireless

Ultra Low Power Radios

Energy Harvesting: Heat

Energy Storage

ULP Electronics

Flexible Antenna

Textiles/Wearability

SAP 1.0

System requirements
- high energy harvesting
- high capacity storage
- ultra-low power consumption
- Integrated ECG electrode
- always on ECG & motion
- industry standard wireless

Ultra Low Power Radios

Energy Harvesting: Heat

Energy Storage

ULP Electronics

Flexible Antenna

Textiles/Wearability

SAP 1.0
**System requirements**
- ultra-low power consumption
- comfortable wearability
- optimized sensor location
- time synchronized sensing
- reliable, repeatable measurements

**Data Activity Identification**

**Data Algorithms**

**Low Power Ozone**

**Low Power VOC**

**Low power PPG**
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Testbed Validation in Lab & Clinical Settings

Phase

0 & I

Proof of concept & Safety

N ~ 10s

Stages

Technology Readiness

Testing Environment

TRL 1: Basic Research

Principles postulated (Theoretical)

TRL 2: Technology Development

Concept/application formulated (Theoretical)

TRL 3: Feasibility Demonstration

Proof of Concept Testing in Laboratory

TRL 4: Lab-Scale Development

Prototype Testing in Laboratory

TRL 5: Technology Development

Early Prototype in Simulated Environment

TRL 6: Viability Demonstration

Advanced Prototype in Simulated Environment

II

Efficacy

N ~ 10s - 100s

TRL 7: Commercial Transition

Advanced Prototype in Real World

III

Randomized Blind Testing

N ~ 1000s

TRL 8: Commercial Demonstration

Commercial Product in Real World

IV

Post-Market Analysis

N ~ 100ks

TRL 9: Commercial Deployment

Success Proven in Real World
Testbed Validation in Lab & Clinical Settings

- Clinical study design with stakeholders of engineered system:
  - medical doctors (clinical practitioners) and researchers
  - patients (especially asthmatic adolescents)
  - systems engineers
  - data & citizen scientists
  - entrepreneurs from academia and industry

  **simulated environment protocol design**

- Clinical experiments with recruited subjects (IRB approved)
- Open-source database development
- Data exploration for novel features, correlations, causations
- Prediction of exacerbation onset accurately and real-time
1. Get customer input through value proposition canvas
2. Translate customer needs to technical requirements for Testbeds
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Prototype Delivery & Scale-Up Examples

Michelle Hernandez
Medical Advisor, Adolescent asthma

Randall Moorman,
Medical Advisor, Cardiac Health

- **SAP 0.9, HET 1.0 Deployments**
  - Dialog ECG shirt system comparison w/Holter
  - Viemetrics collaboration for ~10 HET sensor systems
  - Patient deployment for HET w/Michelle Hernandez

- **Exploring HET 1.0 scale-up in ~2019**
  - Wrist system with ozone and/or VOC sensing
  - 150 units over 9-12 month deployment
  - Cohort that uses rescue inhaler

- **Design iterations on ECG shirt**
  - Custom designed and worn by SAS staff
  - Feedback led to current ECG shirt design

- **SAS ESP data platform at NC State**
  - Create portal for any NCSU members’ use
  - Paperwork in process

- **Associated Funding: Y7 and beyond**
  - NSF, DoD, Army, etc.
  - SBIR/STTR grants
  - Industry sponsorship
  - Core goal of sustainability
Key HET generation features are being fed to SAP Testbed
Mature sensor technologies (ozone, ppg) and electronics are being pushed into higher TRL levels through new funding while still provide needs for Testbeds.
These new efforts are being pursued to create clinical partnerships, scale-up, industry interactions and new proposals
HET 1.0: Viemetrics for ten prototypes
Submitted two PFI grants last year
Submitted several NIH R01 and R21 Grants
DoD/FDA grants for higher TRL levels
Grants with industry members
iCorps
Years 6 – 10 Major System Goals

**Large energy harvesters/Large form factors**

**SAP 1.0**
- **ECG Shirt**: integrated electronics
- ASSIST TEGs, ASSIST flexible heat sinks
- ASSIST Supercaps
- ASSIST SoC/Radio/Antenna
- Sensors: ECG and motion
- Wearability: ECG integrated garment
- Data: Intelligent HR/HRV with motion

**HET 1.0**
- **Chest patch and wrist band**: Battery powered
- COTS SoC/Radio
- Sensors: ECG, PPG, ozone, VOCs, motion, temp, pH, microphone
- Wearability: 3D printed polymers
- Data: Noise correction in ECG

**SAP 2.0**
- **Textile garment and wrist band**: with thermoelectrics, piezo
- ASSIST SoC/Radio/Antenna
- Sensors: ECG, PPG, ozone, VOCs, motion, temp, pH, microphone
- Wearability: watch and shirt
- Data: condition tracking

**HET 2.0**
- COTS potentiostat SoC
- Sensors: glucose/lactate, uric acid through sweat/ISF
- Data: tracking, correlation, and causality

**SAP 3.0**
- **Watch or body-worn patch**: COTS or ASSIST/Psikick SoC
- Sensors: medication in sweat
- Wearability: reduced platform size
- Data: fusion of contextual data

**Small energy harvesters/Integrated form factors**

**HET 3.0**
- COTS or ASSIST/Psikick SoC
- Sensors: medication in sweat
- Data: tracking, correlation, and causality

**Small Form Factors/Long Life/Multimodal**

**SAP 2.0**
- **Textile garment and wrist band**: with thermoelectrics, piezo
- ASSIST SoC/Radio/Antenna
- Sensors: ECG, PPG, ozone, VOCs, motion, temp, pH, microphone
- Wearability: watch and shirt
- Data: condition tracking

**HET 2.0**
- COTS potentiostat SoC
- Sensors: glucose/lactate, uric acid through sweat/ISF
- Data: tracking, correlation, and causality

**HET 3.0**
- COTS or ASSIST/Psikick SoC
- Sensors: medication in sweat
- Data: tracking, correlation, and causality

**Increasingly sophisticated sensing:**
Biochemical/medication etc. and with long battery life

**Years 6 – 10 Major System Goals**

**Year 6**
- **SAP 1.0**
- **HET 1.0**

**Year 7**
- **SAP 2.0**
- **HET 2.0**

**Year 8**
- **SAP 3.0**
- **HET 3.0**

**Year 9**
- **SAP 2.0**
- **HET 2.0**

**Year 10**
- **SAP 3.0**
- **HET 3.0**
Years 6 – 10 Yearly Milestones: HET

**HET 1.0:**
- chest patch and wristband at TRL 5-6/deployable level (Viometrics collab)
- deploy w/ Michelle Hernandez Y6/7

**HET 2.0:**
- systems fully integrated benchtop @ Y6 site visit
- wearable potentiostat

**HET 3.0:** feasibility study for medication detection (and glucose, lactate) in sweat, ISF
- platform feasibility direction (direct medication detection, proxy material, etc.) set from Y7/beg
- sensor system research for maturity by Y8-9/end

**HET 3.0:** sensor system maturation & wearability (HET 2.0)
- wearable system by Y9 site visit; deployable Y10

**HET 2.0:**
- systems wearable and detecting body fluid-based analytes
- deployment-level work (packaging, repeatability) through associated grants, industry in Y9/10

**HET asthma:** associated funding for use case (further health study deployment; system maturation)
- clinical feasibility in hospital, wound clinics in Y8
- wearable system by Y9 site visit; deployable Y10

Sensor maturation shifts to SAP 2.0
Sensor maturation shifts to SAP 3.0; platform maturation shifts to HET 3.0
## Years 6 - 10 Yearly Milestones: SAP

<table>
<thead>
<tr>
<th>Year 6</th>
<th>Year 7</th>
<th>Year 8</th>
<th>Year 9</th>
<th>Year 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAP 0.9: deployment at UVA Medical versus Holter</td>
<td>SAP 0.9: wider scale ECG shirt system deployment</td>
<td>SAP Afib: associated funding for use case (larger deployments, scalable SoC, etc.)</td>
<td>SAP 2.0: self-powered wearable ozone/VOC/ppg system deployment</td>
<td>SAP 2.0: associated funding (EPA, DoD, citizen science, etc.)</td>
</tr>
<tr>
<td>SAP 1.0: End-to-end ASSIST wearable by Y6 site visit</td>
<td>SAP 1.0: self-powered wearable deployment</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SAP 2.0: - ozone, VOC feasibility - piezo + flexible TEG concept at Y6 site visit</td>
<td>SAP 2.0: - self-powered wrist-worn ozone/VOC/ppg with multimodal harvesting wearable end-to-end by Y8 - small scale laboratory validation w/ UNC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>SAP 3.0: - potentiostat integration - body location study for alternate harvesting modes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>SAP 3.0: - potentiostat-integrated ASSISTSoC system - vigilant monitoring electronics with replaceable hydrogel/nanocellulose body interface</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
ASSIST Engineered Systems and Testbeds Roadmap is shaped by its interaction with the Industry.

ASSIST’s goal is the commercialization of the research products and this can be done in multiple ways along this Roadmap:
- Subsystem component level
- Integrated engineered system level
- Collected data and database level

Various federal funding and support mechanisms are also available to push the commercialization opportunities forward.

ASSIST urges all its IAB members for an active interaction towards helping to shape the roadmap and commercialize the products in an partnership.
Questions?
Thank you!

2018 ASSIST Industry Meeting
January 18-19, 2018
Raleigh, NC
ASSIST.NC.SU.edu