THE ENGINEERING RESEARCH CENTER FOR WIRELESS INTEGRATED MICROSYSTEMS

A TEN-YEAR FANTASTIC VOYAGE

Ken D. Wise
ERC Director

ERC Site Visit and Celebration
May 18, 2010
The WIMS ERC was formed recognizing that technology was approaching a tipping point. By combining six things, a flood of advances could be unleashed to improve health care, the environment, the national infrastructure, and other areas, changing the way we live and improving the quality of life.

**THE WIMS ERC HAS BEGUN THIS REVOLUTION**
WIRELESS INTEGRATED MICROSYSTEMS (WIMS)

High-performance microsystems combining

MEMS
PACKAGING
NANOSTRUCTURES
WIRELESS INTERFACES
ADVANCED POWER SOURCES
MICROPOWER INTEGRATED CIRCUITS

COUPLING MICROELECTRONICS TO THE NON-ELECTRONIC WORLD
WIRELESS INTEGRATED MICROSYSTEMS: The Autonomous Gathering of Information

- Focus for Microelectronics in the “More than Moore” Era
- Key to Meeting the Challenges of the 21st Century
PARTICIPANTS IN THE WIMS ERC

- Core Faculty 49
- Outreach Faculty (MSIs) 8
- Universities 10
- Departments/Disciplines 16
- Major Faculty Awards and Honors >20

University of Michigan
Michigan State
Howard University
North Carolina A&T
University of Utah
Michigan Tech
University of Puerto Rico Mayaguez
Prairie View A&M
Spelman College
Tulane

Lead Institution
Core Partner
Collaborating (Outreach Institution)
PUBLICATIONS OF THE WIMS ERC

• Journal Articles Published 346
• Archival Conference Papers 811
• Major Invited Journal Articles >10
• Invited Keynote Presentations >25
ERC IMPACTS ON EDUCATION

• The WIMS ERC has made extensive contributions to education, graduating over 150 PhDs to date. Five new microsystems courses have been created to form the cornerstones of UM M.Eng. and Certificate programs.

• The multi-year Integrated Microsystems Enterprise program at Michigan Tech has enrolled >175 students to date, with 79 graduations.

• The ERC has offered 72 K-12 short courses to date, enrolling 3424 students (including (for 7-12) 1055 women and 1319 minorities) and changing many lives. Over 60% of HS graduates have entered college in engineering.

• WIMS is an ideal tool for encouraging more of our young people to pursue careers in science and engineering, addressing what is increasingly recognized as a critical national problem.
WIMS K-12 SHORT COURSES
(of 2149 7-12 Students: 61% underrepresented, 49% female)

NSF ERC for Wireless Integrated MicroSystems (WIMS)
WIMS UNDERGRADUATE PROGRAMS

• Undergraduates are now routinely involved in graduate research, reaching well over 100 students per year and aided by programs such as REU, LSAMP/REU, WUGR, and REU/WUGR.

• The Integrated Microsystems Enterprise (IME) program at Michigan Tech is a multi-year undergraduate project experience engaging teachers and delivering data-gathering hardware to seven Upper-Peninsula high-schools. It has involved over 175 students to date.
WIMS ERC NEW COLLEGE COURSES

M.Eng. Degree
• 30 credit hours
• Course options in mgmt. & mfg.
• Practicum with industrial mentor

CASE Certificate
• 15 credit hours
• Wide choice of engineering courses

Engineering & Science Students (Grad & UG)

EECS 414
Introduction to MEMS

EECS 413
Monolithic Amplifiers

EECS 427
VLSI Design I

EECS 425
MEMS/Integ. µSys Lab

MTU ENT 19xx, 29xx, 39xx, 49xx
Integrated Microsystems Enterprise

MTU ME 4640/5640
Micromanufacturing Processes

MTU EE 5470
Semiconductor Fabrication Technologies

EECS 830
Societal Impact of Microsystems

EECS 414
Adv. MEMS Dev. & Tech.

EECS 515
Adv. Integrated µSystems

EECS 511
Analog/Digital Interface Circuits

EECS 522
Analog Integrated Circuits

EECS 523
Digital IC Technology

EECS 627
VLSI Design II

Other Courses:
Manufacturing
Optical MEMS
Wireless Communication
Environmental Chemistry
Business Fundamentals
Patent Law

1,317 UM Students
+724 Dist.Ed.

Key:
Undergraduate
Graduate

EECS 427
VLSI Design I

EECS 509
BioMEMS

1,317 UM Students
+724 Dist.Ed.

Key:
Undergraduate
Graduate

EECS 427
VLSI Design I

EECS 509
BioMEMS

1,317 UM Students
+724 Dist.Ed.

Key:
Undergraduate
Graduate

EECS 427
VLSI Design I

EECS 509
BioMEMS

1,317 UM Students
+724 Dist.Ed.

Key:
Undergraduate
Graduate

EECS 427
VLSI Design I

EECS 509
BioMEMS

1,317 UM Students
+724 Dist.Ed.

Key:
Undergraduate
Graduate

EECS 427
VLSI Design I

EECS 509
BioMEMS

1,317 UM Students
+724 Dist.Ed.

Key:
Undergraduate
Graduate
**WIMS INTERNATIONAL COLLABORATIONS**

- Formal (MicRO) Alliance with the University of Freiburg and the University of Kyoto
- Model for activities at IME Singapore
- Research interactions with IME, IMEC, KAIST, KIST, ETH, Freiburg, Seoul National, Shanghai Jiao Tong …
- Courses offered at the University of Freiburg, University of Kyoto, University of Lille, Middle East Technical University, …

**SERVICE**

- Clark Nguyen served 3 years as MEMS Program Manager, DARPA/MTO
- Yogesh Gianchandani served 2 1/2 years as Micro/Nano Program Manager at NSF
- Richard Brown became Dean of Engineering at the University of Utah, where he continues to direct a component of WIMS research
WIMS GRADUATE RESEARCH AND IMPACT

• Graduated over 150 WIMS PhDs to date

• Led developments in WIMS to where it is now a major focus for industry in the “More than Moore” era

• Authored invited papers at virtually every major MEMS/microelectronics conference, including IEDM (3), Sensors Expo, ISCAS, MRS, MTT, EMBS, COMS, Hilton Head, NSTI Nanotech, ISSCC (3), SPIE, ISCC, IROS, AVS, CICC, Euroensors, Transducers (4), Oliphant CMB, VLSI Circuit Symposium, µTAS, and DRC. Many of these talks were plenary.


PRODUCTS OF THE WIMS ERC

- Industrial Members: 38
- Affiliate Members (Sandia): 1
- Contributing Members: 7
- Spin-off Companies Formed: 11
- Invention Disclosures: 103
- Patents Awarded: 59
WIMS START-UP COMPANIES

**Sensicore** (Water Quality Sensing; ---> GE)  2000

**Discera** (Integrated MEMS Communications Transceivers)  2001

**Mobius Microsystems** (MEMS Clocking, ---> IDT)  2002

**PicoCal** (Thermal Microsystems; Microcalorimetry)  2003

**NeuroNexus Technologies** (Neural Interfaces)  2004

**NanoBrick** (MEMS Educational Products)  2006

**ePack** (MEMS Packaging)  2007

**Sakti3** (Battery Technology)  2007

**Enertia** (Energy Harvesting)  2010

**Ambiq Micro** (Ultra-Low-Power Microsystems)  2010

**Structured Microsystems** (Implantable Microsystems)  2010
OTHER UNIVERSITY OF MICHIGAN MEMS/MICROSYSTEM START-UPS

**Integrated Sensing Systems (ISSYS)** 1995
Pressure and Flow Instrumentation; Medical Products

**HandyLab** 1999
DNA/Genetic Instrumentation; (----> Becton Dickenson)

**Ardesta** 2000
Venture Capital; MEMS Commercialization

**Sonetics** 2003
Infrared and Ultrasonic Imaging Systems

**Accuri Instruments** 2004
Microflowmeters and Flow Cytometers

**Evigia Systems** 2004
RFID Technologies and Sensing Microsystems
RESEARCH ACTIVITIES

• Organized in Five Thrusts Areas
  – Micropower Circuits
  – Wireless Interfaces
  – Advanced Processes/Packaging
  – Biomedical Sensors
  – Environmental Sensors

All Producing Results that Define the State of the Art

• Typically over 100 Projects
• NSF Core Support Typically One-Fourth of Total
• Projects are Linked by Testbeds
  – Active Cardiovascular Stent
  – Intraocular Pressure Sensor
  – Cochlear and Cortical Neural Interfaces
  – Environmental Monitoring Microsystem
WIMS MICROCONTROLLER EVOLUTION

WIMS Gen-1 Microcontroller
- TSMC 0.18µm MM/RF bulk CMOS
- 3.5 million transistors
- Core+mem: 33.9mW @ 1.8V & 92MHz
- Core+mem: 1.41mW @ 1.15V & 10MHz
- MEMS clk: 17.28mW @ 1.8V & 200MHz
- Sleep mode: 740µW @ 1.1V

WIMS Gen-2 Microcontroller
- TSMC 0.18µm MM/RF bulk CMOS
- 2.3 million transistors
- Core+mem: <20mW @ 100MHz
- Core+mem: <1mW @ 10MHz
- Ring clk: <1mW @ 20MHz
- Sleep mode: <50µW
- DSP runs CIS

Professor Richard Brown
**PHOENIX: A 30pW Platform for Sensing Applications**

- Minimizes sleep energy to realize the world’s lowest-power processors
- The Phoenix microprocessor has been designed with comprehensive sleep strategy
  - Unique power gating approach
  - Event-driven CPU with compact instruction set
  - H/W supported compression
  - Low leakage SRAM cell
  - Adaptive leakage management in DMEM
- Measurements
  - $P_{\text{sleep,avg}} = 30\text{pW}$
  - $E_{\text{active}} = 2.8\text{pJ/Inst}$ at 0.5V
  - $P_{\text{sram}} = 10.9\text{fW/bit}$ (retentive)
  - 915 x 915µm$^2$ in TSMC 0.18µm
  - 10 yr lifetime with 1mm$^2$ thin-film battery

*Professor Dennis Sylvester*
AN 0.13µM CMOS 2.4GHZ ISM BAND SUPER REGENERATIVE RADIO

The first fully integrated super-regenerative radio

<table>
<thead>
<tr>
<th>Feature</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply</td>
<td>1.2 V</td>
</tr>
<tr>
<td>Supply current</td>
<td>2.5 mA</td>
</tr>
<tr>
<td>Area</td>
<td>1mm²</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>-90 dBm</td>
</tr>
<tr>
<td>Data rate</td>
<td>&lt; 500 Kbits/s</td>
</tr>
<tr>
<td>Channel spacing</td>
<td>10 MHz</td>
</tr>
<tr>
<td>BER</td>
<td>&lt; 1/1000</td>
</tr>
</tbody>
</table>

- Record energy efficient ~ 5.8nJ/bit
- New multi-channel architecture with excellent selectivity

Professor Michael Flynn
ON-CHIP ANTENNAS

World Record Size and Efficiency for an On-Chip Antenna

<table>
<thead>
<tr>
<th>Antenna Type</th>
<th>Gain [dBi]</th>
<th>$f_r$ [GHz]</th>
<th>Max. Linear Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>This work</td>
<td>-10.0</td>
<td>9.0</td>
<td>780 µm</td>
</tr>
<tr>
<td>Dipole Ant. [1]</td>
<td>-31.2</td>
<td>7.4</td>
<td>2000 µm</td>
</tr>
<tr>
<td>Zig Zag Ant. [2]</td>
<td>-17.0</td>
<td>15.0</td>
<td>2000 µm</td>
</tr>
</tbody>
</table>

Gain vs. Frequency [GHz]

Professor Kamal Sarabandi
**WIRELESS INTEGRATED SENSING PLATFORMS**

**2006: WIMS Narada Nodes**
- 16b ADC resolution on four channels
  - ISM band transceiver (802.15.4)
  - Range: 300m, Data Rate: 250Kbps
  - Sample Rate: 100kHz
- Volume 60cc
- Power 200mW

**2010: Single-Chip Nodes**
- On-chip vapor/temp sensors
- Wireless on-chip transceiver
- On-chip antenna
- Single chip, Volume < 0.002cc
- Power: 2mW/1µW/1nW

Professors Michael Flynn, Jerome Lynch, and Dennis Sylvester
NARADA-BASED INFRASTRUCTURE MONITORING

Grove Street Bridge, Ypsilanti, Michigan (2005)
18 wireless sensors measuring acceleration and displacement

Geumdang Bridge, Korea (2005 - present)
16 wireless sensors measuring acceleration

Voigt Bridge, San Diego, California (2006)
20 wireless sensors measuring acceleration

Wu Yuan Bridge, China (2005 - present)
8 wireless sensors measuring acceleration

Professor Jerome Lynch
ACTIVE CARDIOVASCULAR STENTS
Wireless Readout of Intra-Arterial Blood Pressure/Flow on Demand

D. Dehennis
K. Takahata
Y. Gianchandani
K. Wise

Detects flow drops >13% due to re-stenosis in the carotid arteries.
A WIRELESS INTRAOCULAR PRESSURE SENSOR FOR TREATING GLAUCOMA

• Intraocular pressure is a significant key in treating glaucoma, the second-leading cause of blindness, affecting 65 million worldwide
• Sensor will take readings every 15min, storing them in memory
• Powered by energy scavenging; read out once a day over an UWB link
• Integrates the pressure sensor, rechargeable microbattery, wireless link, and embedded processor in a parylene-covered glass package
• Size: 0.5mm x 1mm x 2mm
• Phoenix processor holds data at 30pW; operates at 300nW.

Razi Haque, Ken Wise, Dennis Sylvester, Paul Lichter
A GLASS-IN-SILICON PROCESS FOR THE INTRAOCULAR PRESSURE SENSOR

Hermetically-sealed pressure sensors in glass packages on a U.S. penny
Sensitivity: 25fF/mmHg
Resolution: 0.2mmHg
Range: 600-900mmHg
Linear Response
ANATOMY OF A COCHLEAR PROSTHESIS

Over 150,000 cochlear prostheses have been implanted to date.

250 million people worldwide are classified as disabled due to hearing loss.

External Transmitter Coil

Receiver/Stimulator

Ball Reference Electrode

Wire Electrode Bundle

Speech Processor (worn behind the ear)

Courtesy of Cochlear Corporation
A HIGH-DENSITY COCHLEAR MICROSYSTEM

Thin-film electrode technology; up to 128 high-density IrO sites
Embedded sensors for array position and wall contact
Biocompatible silicon-quartz-parylene structure; integrated 8-lead microcable
Articulated insertion tools being developed to allow deep placement

All Firsts

A Five University Collaboration
A triple-parylene process provides flexibility, robustness, and the biocompatibility needed for long-term implants. **Molded and monolithically-formed backings are in development**
CORTICAL MICROSYSTEMS: Electronic Interfaces to the Nervous System

Gateway to Prostheses for:
- Deafness
- Blindness
- Epilepsy
- Paralysis
- Parkinson’s Disease
A LOW-PROFILE HIGH-DENSITY CORTICAL ARRAY
64 Sites on 200µm Centers Instrumenting 1mm³

- World-leading technology for neural interfaces
- Driving revolutionary advances in neuroscience
- Foundation for neural prostheses for treating
  - Deafness
  - Blindness
  - Epilepsy
  - Parkinson’s Disease
  - Paralysis

1mm x 1mm x 0.5mm with 4mm long shanks
DIAMOND NEURAL PROBES

Earlier Diamond Probes:
EC Potential Window = 3V

Diamond Single Material MEMS (SMM) Probe:
EC Potential Window = 4 V

Electrode Diameter = 10-150μm

Nor-epinephrine Detection

Recordings in Guinea Pig Auditory Cortex in Response to Acoustic Stimulation

Stimulus

10μV 500 ms

Noise
LATTICE PROBES: Scaling to Cellular Dimensions
UNDERSTANDING THE FOREIGN-BODY RESPONSE

Horizontal Section at 8 weeks Post-Implant

“Tissue integrates into the lattice probe and in some cases viable neurons are very close to structures”

Collaborators: John Skousen and Prof. Patrick Tresco, University of Utah
**SOLID VS. LATTICE SHANKS: HORIZONTAL SECTIONS**

“Distance from electrode face to end of ED-1 positive zone greater on solid vs. lattice probe”

IgG IgG antibodies, **ED-1** Activated microglia/macrophages, **DAPI** Cell nuclei

8 weeks post-implant

![Images showing comparison of solid and lattice shanks](image-url)
For both ED-1 (microphages) and IgG (blood-brain barrier) staining, the extent of the reaction zone is greatly reduced along with the amount of reaction.

For the blood-brain barrier, the reduction is much more dramatic than for macrophages, reaching a peak of only 15 within the lattice holes themselves.
A 5-PROBE 160-SITE ARRAY FOR CN MAPPING

Sr. Mary Elizabeth Merriam
Prof. Susan E. Shore
Frequency tuning seen across the VCN rostral-caudal tonotopic axis.

Enabling Breakthroughs in our Understanding of the CNS
# MEDICAL COLLABORATORS

with thanks to

<table>
<thead>
<tr>
<th>Name</th>
<th>Institution</th>
<th>Field</th>
</tr>
</thead>
<tbody>
<tr>
<td>James Baker</td>
<td>University of Michigan</td>
<td>Cell Sorting</td>
</tr>
<tr>
<td>György Buzsáki</td>
<td>Rutgers University</td>
<td>Systems Neurophysiology</td>
</tr>
<tr>
<td>Daniel Hayes</td>
<td>University of Michigan</td>
<td>Cancer Screening</td>
</tr>
<tr>
<td>Paul Lichter</td>
<td>University of Michigan</td>
<td>Intraocular Implants</td>
</tr>
<tr>
<td>John Middlebrooks</td>
<td>UC — Irvine</td>
<td>Auditory Implants</td>
</tr>
<tr>
<td>William O’Neill</td>
<td>Beaumont Hospital</td>
<td>Active Stents</td>
</tr>
<tr>
<td>James Patrick</td>
<td>Cochlear Corporation</td>
<td>Cochlear Implants</td>
</tr>
<tr>
<td>Bryan Pfingst</td>
<td>University of Michigan</td>
<td>Cochlear Implants</td>
</tr>
<tr>
<td>Ken Pienta</td>
<td>University of Michigan</td>
<td>Cell Sorting</td>
</tr>
<tr>
<td>Robert Shannon</td>
<td>House Ear Institute</td>
<td>Cochlear Implants</td>
</tr>
<tr>
<td>Susan Shore</td>
<td>University of Michigan</td>
<td>CN/VCN Mapping</td>
</tr>
<tr>
<td>Russell Snyder</td>
<td>UC — San Francisco</td>
<td>Cochlear Implants</td>
</tr>
<tr>
<td>Patrick Tresco</td>
<td>University of Utah</td>
<td>Foreign Body Response</td>
</tr>
<tr>
<td>Blake Wilson</td>
<td>Duke University</td>
<td>Speech Coding</td>
</tr>
</tbody>
</table>
A 32-CHANNEL DIGITAL SPIKE DETECTOR

- Accepts/digitizes 32 multiplexed channels to 5b; calculates per-channel means and standard deviations; sets biphasic thresholds; transmits signals at 2.56Mbps.
- Identifies spikes, saving 10-15X in system bandwidth and increasing the number of channels from 25 to 312.
- Operates at 1.2mW from a 3V supply and a 2.56MHz clock with a die size of 2mm x 3mm.
A 32-CHANNEL MIXED-MODE PROCESSOR

Scan mode: Transmits addresses of active sites
Monitor mode: Digitizes and transmits the full spike shape
A FIRST-GENERATION CORTICAL MICROSYSTEM

Monitor and scan modes; 64 channels: Programmable threshold, gain, and LF cutoff; Output data rate: 64kS/sec@2MHz clock, 2Mbps; Per-channel gain: 1000

Demonstrated functionality but too big and too many bonds.
A SECOND-GENERATION CORTICAL MICROSYSTEM

Stimulation mode;
Monitor and scan recording modes;
Site Selection;
32 recording channels;
16 stimulating channels;
Programmable per-channel threshold;
Output data rate: 64kS/sec@2MHz clock, 2.5Mbps;
Nominal per-channel gain: 1000
GAS CHROMATOGRAPHY: Separation and Identification of Complex Gaseous Mixtures

Table-top instruments that offer precision analysis but are relatively expensive, slow, and not portable enough for field use.

The WIMS µGC
100X Smaller
100X Cheaper
100X Faster

TARGETED PERFORMANCE:

- 30-50 Organic-Vapor Pollutants per Analysis
- Detection Levels: <1ppb per analyte
- Analysis time: 5-50sec
- Size: 5-50cc
μGCs FOR COMPLEX GASEOUS MIXTURES

(2003) Single column

(2006) Dual-column (tunable)

(2009) Comprehensive μGC x μGC

(2010)

Mercury
ENABLING TECHNOLOGIES

High-capacity, low-mass preconcentrators

High-resolution, low-mass µcolumns

High-volume micropumps

High-sensitivity nano-arrays
Detector, 50cm column, and single-bed precon on a U.S. quarter
SEPARATION OF SIX TUBERCULOSIS
BIOMARKERS FROM 30 INTERFERENCES

Analysis conditions
- Carrier gas: Air
- Split: splitless
- Inlet: 200ºC, 8 psi
- Column: two 3m
- Flow: 0.3mL/min
- Detector: FID

Biomarkers
1. 1-dimethylcyclohexane (cis)
2. 1-dimethylcyclohexane (trans)
3. 3-heptanone
4. 2,2,4,6,6-pentamethylheptane
5. 1-methyl-4-(1-methylethyl)-benzene (p-cymene)
6. 1-methylnaphthalene
DETECTION OF EXPLOSIVES

INTREPID μGC

- Partial separation coupled with sensor-array pattern permits determination of nitroaromatic explosives
- LOD (2,6-DNT) = 35ppt!

n-pentadecane

2,3-dimethyl-2,3-dinitrobutane

2,4-dinitrotoluene

2,6-dinitrotoleune

Time (min)
A FULLY-INTEGRATED MERCURY MICROSYSTEM

Mercury µGC with preconcentrator, 50cm separation column, and detector. Temperature sensors, heaters, drivers, processor, memory, USB interface.

Robert J. M. Gordenker
Hassan Lajihi
Pushing the limits to reduce size, analysis time, and power.
THE ORION \(\mu\text{GC}\)

On an Apple “Shuffle” MP3 Player

Circle is about the size of a U.S. quarter
IMPACTS

The WIMS ERC has:

– Graduated over 150 doctoral students; offered short courses enrolling over 3500 pre-college students, with 60% selecting engineering careers.
– Created 11 startups, with an impact on the State estimated at over $400M.
– Led a worldwide revolution in microsystems and its core technology areas.
– Demonstrated low-cost widely-deployable radiation detectors for ensuring the safety and integrity of containerized shipping worldwide.
– Sparked worldwide efforts to develop neuro-electronic interfaces for neuroscience and neural prostheses.
– Realized the first thin-film cochlear electrode arrays, with the prospect of providing improved hearing to millions.
– Developed smart air-quality monitors to help address global warming.
– Demonstrated hand-held breath analyzers for biomarkers of tuberculosis and lung cancer, for use in developed and undeveloped areas of the world.
Technology has passed a tipping point. By combining micropower circuits, sensors, wireless interfaces, power sources, packaging, and nanostructures, WIMS has unleashed a flood of advances for health care, the environment, the national infrastructure, and other areas that will change the way we live and improve the quality of life.

The WIMS Institute will continue to drive core research in microsystems and their use in addressing critical national needs.