Transforming Ordinary Buildings into Smart Buildings via Low-Cost, Self-Powering Wireless Sensors & Sensor Networks

2016 Building Technologies Office Peer Review

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Project Summary

Timeline:
Start date: 10/01/2014
Planned end date: 09/30/2014

Key Milestones
1. Design Energy Harvesting ASIC; 12/31/2014
2. Tapeout ASIC and Test Circuit; 6/30/2015
3. Complete Sensor Node; 9/30/2015

Key Partners:

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<th>Intwine Connect</th>
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Budget:

Total Project $ to Date:
- DOE: $405,356.59
- Cost Share: $60,309.76

Total Project $:
- DOE: $749,990
- Cost Share: $103,012

Project Outcome:
The objective of this project is to design and demonstrate a low-cost, compact, easy-to-deploy, maintenance-free sensor node technology, and a network of such sensors, which enable the monitoring of multiphysical parameters and can transform today’s ordinary buildings into smart buildings with environmental awareness.

We have developed the proposed sensor node, and have integrated it with the network, and are making solid progress on development and commercialization.
Purpose and Objectives

Problem Statement: A low-cost solution is needed in transform today’s ordinary buildings into smart buildings. Battery-Powered wireless sensors require periodic replacement of battery (high maintenance cost) and generate large amount of battery waste at end of lifespan (environmental threat). Our technology can address these issues.

Target Market and Audience: Our technology allow BEMS integrators to provide highly competitive smart building solutions to end customers. The BEMS market is $2.4 billion in 2015, and advanced sensor market market is $1.2 billion in 2016.

Impact of Project:
1. The final product of this project is a low-cost, compact, easy-to-deploy, maintenance-free sensor node technology, and a network of such sensors,
2. The technology developed can enable the monitoring of multiphysical parameters and can transform today’s ordinary buildings into smart buildings with environmental awareness, and is expected to take a substantial market share in the smart sensors for BEMS.
   a. Near-term outcomes: alpha prototype complete and start formulating business plan based on the developed technology.
   b. Intermediate outcomes: beta prototype complete and validated with independent third party/potential customer.
   c. Long-term outcomes: startup company established and product taking a large BEMS market share.
**Approach**

**Approach:** We leverage high-efficiency energy harvesting and ultra-low power circuits to achieve self-powering wireless temperature sensors.

**Key Issues:** The key issue is to generate sufficient power from harvesting the vibration energy from the environment, and minimize the energy consumption in the sensor operation.

**Distinctive Characteristics:**

The uniqueness of our energy-harvesting technique is that we focus not just on steady vibrations, but also on harvesting energy from all the transient vibrations such as door closing.

The uniqueness of our ultra-low power design is that it can minimize power consumption during normal operation, and use the most energy-efficient scheme for wireless data transmission.
Approach: System Architecture for the Sensor Node

- **Optional Alternative Energy Source**
  - Battery Pack
  - RF Harvester
  - Solar Cell
  - Thermal Harvester

- **Energy Harvesting ASIC**

- **Power Bus**

- **RF MCU CC2530**

- **Signal & Control Bus**

- **One or More Sensors (Multiple Sensor Interfaces Available on Main Board)**
  - Temperature
  - Pressure
  - Humidity
  - Light
  - Occupancy

- **Alternative Power Interface**
  - Piezoelectric Device
  - Vibration Energy Harvesting
Progress and Accomplishments

Accomplishments: We have achieved:
Self-powering sensor nodes, harvesting vibrational energy in indoor environments. Wireless connectivity through standard ZigBee network. Self-powering wireless temperature sensing using the sensor node and network. See Quarterly Breakdown for more details.

Market Impact:
1. To ensure & accelerate impact, the technology is timely disseminated through peer-reviewed publications, conference presentations, and patent applications. In addition, business plans are developed based on the technology and we have actively participated in many business competitions, and have achieved surprisingly successful results.
2. The actual impacts exceed the planned impacts, in that the business competitions based on the developed technology has been highly successful. See Quarterly Breakdown for more details.

Awards/Recognition: See Quarterly Breakdown for more details.
Q1 Progress and Accomplishments

We have completed the design of the Application Specific Integrate Circuit (ASIC), a key enabling component, for this application.
Q1 Progress & Accomplishments Toward Commercialization

• IP: the 1st patent on this project is being filed, more disclosures in prep.
• PI’s students’ team won 2015 Clean Energy Challenge at CWRU.
• Team selected to compete in Chicago for 2015 Clean Energy Challenge.

Interdisciplinary CWRU Team (for the Chicago competition) Included:
• Engineering
• Business
• Economics
• Materials Science
Q2 Progress and Accomplishments

We have demonstrated wireless temperature sensing by using a commercial wireless sensor entirely powered with our piezoelectric harvester. We also completed the calibration of different vibrational surfaces for PZE energy harvesting.
Q2 Awards/Recognition

The work in demonstration of wireless temperature sensing powered by PZE vibrational energy harvesting) is accepted in and presented at the IEEE International Frequency Control Symposium (IFCS 2015), the flagship IEEE conference in electromechanical resonant transducers. The full-length publication is published in the conference proceedings.

Based on his work during this part of the project, high school student Robert Gray (under the supervision and support from Dr. Peng Wang & Dr. Philip Feng) has won the Grand Prize at this Spring's Northeastern Ohio Science & Engineering Fair (NOSEF), ranking the 1st place for the Engineering category at NOSEF, receiving plaques and certificates from CSA, SPIE, and Parker Hannifin.
Q2 Progress & Accomplishments Toward Commercialization

• Clean Energy Challenge 2015 (Clean Energy Trust, Chicago, IL)
  – 14 cleantech startups from seven Midwestern states competed for $1MM in early stage investment funding—our student team (1 Ph.D. student working on this project plus a few undergrads) made to the one of the only 5 student team finalists
  – The event has sold-out crowd of 400 included clean energy investors, entrepreneurs, and innovators—as well as Illinois Governor Bruce Rauner
  – NREL investor event validated market interest
  – Venture groups from BASF, GE, LG, Siemens and Saudi Aramco all expressed strong interest
  – Extensive feedback from mentors and judges (Energy businesses and VCs)
Q3 Progress and Accomplishments

- We have completed the circuit design and produced printed circuit board for the sensor node.
- We also received the ASIC from tapeout and completed the testing.
- We further completed the sensor node and fully verified its functionality using external power.
Q3 Awards/Recognition

The work has been accepted by the 18th International Conference on Solid-State Sensors, Actuators and Microsystems (Transducers’15), the leading international conference in electromechanical transducers, energy harvesters, and novel sensor systems, as a Poster Presentation. Team members traveled to the conference and presented the work.

Battery-Less Wireless Temperature Sensors via Harnessing Household Vibration Energy

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²Hawken Upper School, Gates Mills, OH 44040, USA
³Email: peng.wang@case.edu; philip.feng@case.edu

We report on experimental demonstration of a wireless temperature sensor node (WTSN) powered by a piezoelectric (P2E) resonant energy harvesting system. The energy harvesting circuit collects and stores the energy generated by a piezoelectric resonant transducer into a capacitor, and uses the stored energy to power the temperature sensor and its associated signal processing circuits for wireless signal transmission. The resulting WTSN transmits measured temperature data over a distance of 10m, in real time, and consumes ~4μW to ~13μW power (for transmission intervals from 10min to 10s, respectively), supplied entirely by the P2E resonant energy harvester. Such self-powered WTSNs, when integrated with building energy management system, can enable low-cost transformation of ordinary buildings into energy-efficient smart buildings.
Q4 Progress and Accomplishments

- We have completed assembled the self-powering wireless sensor node.
- We established wireless connection between the sensor nodes and ZigBee gateway.
- We demonstrated self-powering wireless temperature sensing.
Voltage on the super capacitor reflects the total stored energy. When vibrational energy is harvested, it shows as an increase in. When energy is used to charge the output buffer, it shows as a decrease in voltage.

Voltage on the output buffer shows how the sensor node consumes energy. When the ZigBee chip performs wireless data transmission, a sudden drop in voltage is seen. When the voltage fall below a threshold, the ASIC will charge it (from the super capacitor).
Verifying Energy-Harvesting & Ultra-Low Power Operation

**15 minutes of data**

- **ZigBee Idle Power (No Transmission):** slowly drain the voltage on output buffer
- **Energy Harvesting Events (4 such events during the 15 minutes):** sudden voltage drop (energy consumed)
- **Voltage on the Output Buffer**
  - ASIC charges the output buffer (from super capacitor) when voltage below a threshold
  - Data used for calculation (see next slide)
- **Voltage on the Super Capacitor**
  - Minimal voltage drop outside the charging cycles
  - ASIC extracts energy from super capacitor to charge output buffer
  - Energy Harvesting Events (4 such events during the 15 minutes)
  - ASIC extracts energy from super capacitor to charge output buffer after each transmission
Verifying Energy-Harvesting & Ultra-Low Power Operation

- We calibrate the power consumption from the measured voltage drops
  - Wireless transmission (data from the drop at 72.4 min):
    - $V_{\text{begin}} = 2.828\text{V}$, $V_{\text{end}} = 2.503\text{V}$, $\Delta E = \Delta (0.5CV^2) = 8.66 \times 10^{-4}\text{J}$
    - Average power consumption = $8.66 \times 10^{-4}\text{J}/10\text{min} = 1.44\mu\text{W}$
  - Idle power (data from 67.74min to 69.80min)
    - $V_{\text{begin}} = 2.957\text{V}$, $V_{\text{end}} = 2.761\text{V}$, $\Delta E = \Delta (0.5CV^2) = 5.60 \times 10^{-4}\text{J}$
    - Average power consumption = $5.60 \times 10^{-4}\text{J}/(69.80\text{min}-67.74\text{min}) = 4.53\mu\text{W}$
  - Total power consumption
    - $1.44\mu\text{W} + 4.53\mu\text{W} = 5.98\mu\text{W}$
- Test shows that the complete sensor node exceeds the requirement specified in the SOPO (power consumption 7.4\mu\text{W} when the transmission is one per 10 min)
Q5 Progress and Accomplishments

- We have tested wireless functions between the emulator and ICG, which are verified to function as intended.
- We have completed market analysis.

Estimate of unit economics (cost, sales, margin) for the first 5 years after product launch.
Q5 Awards/Recognition

• We have been awarded the Ohio Third Frontier Technology Validation and Start-up Fund (TVSF) as an supplementary resource for validating our self-powering wireless sensor technology and product.

• Our paper “A Self-Powering Wireless Temperature Sensor Node with Low-Power Application-Specific Integrated Circuit (ASIC) and Vibration Energy Harvester” has been accepted for Lecture presentation at the 2016 IEEE International Symposium on Circuits & Systems.
Q5 Progress & Accomplishments Toward Commercialization

- Our startup based on the technology developed under this project, *CrystalE*, has been making substantial progress towards securing venture capital and commercializing the technology:

- During Q5, the team has already:
  - Won 1st place in Case GLEI Clean Energy Business competition
  - Will attend as finalist in Allegheny CleantechUp competition (3/16/2016)
  - Will attend as finalist in 2016 Clean Energy Trust Challenge (4/12/2016)
  - Will attend as finalist in 2016 Rice Business Plan Competition (4/14/2016) (500+ startup teams around the world competed for the 42 finalist position in the competition)
Project Integration and Collaboration

Project Integration: The CWRU team and the Intwine team are both located on CWRU campus (within the same set of interconnected buildings), and have regular meetings to coordinate the progress and make synergetic efforts towards solving technical challenges.

Partners, Subcontractors, and Collaborators: (more in following slides)
- We work closely with Intwine Connect in both technology development and commercialization effort.
- We work closely with Great Lakes Energy Institute (GLEI) in business plan development and competitions.
- We work with Case Master in Engineering Management (MEM) program in product development and market analysis.
- We work with Case Office of Research and Technology Management (ORTM) in IP management and securing additional resource for technology validation.

Communications: see quarterly details.
Team Management Plan

Profs. Philip Feng (PI), Kenneth Loparo (Co-I) Dave Martin (Partner PI)
Dr. Max Wang (Co-I), Dr. Wen Ko (Consultant)

Energy Harvesting
Low-Power ASIC
Wireless Sensors
Packaging

System Integration
Monthly Meeting
Weekly Discuss
Daily Collaboration

Testing
Market
Gateway
User Base

Dave Martin (Partner PI)
Justin Wray (Project Engineer)
Jim Basar (Product Engineer)

Profs. Philip Feng (PI), Kenneth Loparo (Co-I)
Dr. Max Wang (Co-I), Dr. Wen Ko (Consultant)

Peng Wang (Postdoc)
Ph.D. Student
Undergrad Students
High School Interns

U.S. DEPARTMENT OF ENERGY
Energy Efficiency & Renewable Energy
Technical Team

Philip Feng  
PI, Case

Kenneth Loparo  
Co-PI, Case

Dave Martin  
Co-PI, Intwine

Postdoc/Ph.D.
Max Wang  
Peng Wang  
Xuqian Zheng

Engineer
Jim Basar  
Ryan May  
Justin Wray  
Ran Wei

Undergraduate
Amanda Jaworski  
Eric King  
Christopher Herbst

High School Intern
Aman Nair  
Robby Gray  
Geoffrey Miller
Commercialization Team

Postdoc and Ph.D. Student
Max Wang
Peng Wang
Xuqian Zheng

Undergraduate (Business and Management)
Billy Littlefield
Alicia Chang
Jeffrey Brown

Advisors & Partners
Ali Ahmed
Cisco
Bob Sopko
Blackstone
Gordon Yonel
Entrepreneur
Roger Saillant
Fowler Center
Next Steps and Future Plans

Next Steps and Future Plans: (more details in following slide)

• **Device**
  – Implement compact design in circuit board, smaller energy harvester

• **Wireless Function Design**
  – Programming on both sensor node and ICG for low-power automated pairing and data transmission

• **Commercialization**
  – Contact business partners, showcase demonstration prototype
Next Steps and Future Plans

We Are Here (Now)

- Demonstration Prototype
- 1st Generation Prototype
- 2nd Generation Prototype
- Production Prototype
- Multifunction Sensors
- Field Testing with Intwine Partners
- Field Testing with Additional Partners
- Identification of US manufacturers and commercialization partners
- Prototype Demonstration
- Business Competition
- Energy
- Temperature
- Installation Sampling Rate
- Talk to VC and Businesses

REFERENCE SLIDES
Project Budget

Project Budget: FY2015 numbers are End-of-Year numbers as of 9/30/2015. FY2016 numbers are Project-to-Date numbers as of 1/31/2016 (corresponding to the “Total Project $ to Date” numbers in the Summary Slide).

Variances: Overall the expense follows the original planned budget and the project plan has not been modified.

Cost to Date: See table below.

Additional Funding: N/A

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## Project Plan and Schedule

### Project Schedule

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<th>Q2 (Jan-Mar)</th>
<th>Q3 (Apr-Jun)</th>
<th>Q4 (Jul-Sep)</th>
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<th>Q3 (Apr-Jun)</th>
<th>Q4 (Jul-Sep)</th>
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<th>FY2016</th>
<th>FY2017</th>
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<td>Active Task (in progress work)</td>
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- **Milestone/Deliverable (Originally Planned)** use for missed
- **Milestone/Deliverable (Actual)** use when met on time

### Past Work

- Q1 Milestone: Circuit Design
- Q2 Milestone: Energy Harvester
- Q3 Milestone: ASIC Tapeout and Test
- Q4 Milestone: Prototype Sensor Node
- Q1 Milestone: Sensor Node Programming

### Current/Future Work: Sensor Node Testing

- Q3 Milestone: Packaging/Market Analysis
- Q4 Milestone: System Testing/Commercialization