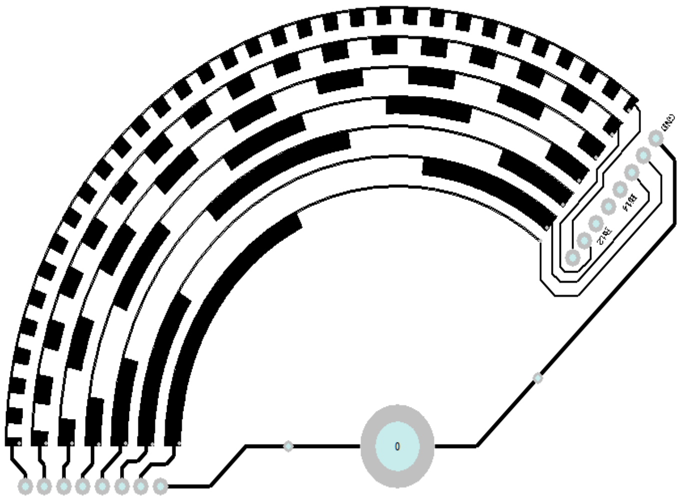
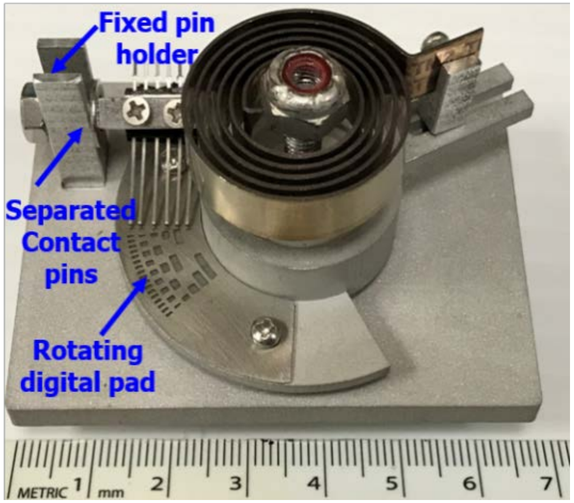
U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

All-Digital Plug and Play Passive RFID Sensors for Energy Efficient Building Control





Clemson University, Harvard University, Phase IV Engineering Inc., Iowa Energy Center
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Project Summary

Timeline:

Start date: 10/01/2016

Planned end date: 12/01/2019

Key Milestones:

1. **Milestone 2.6 (M12):** Prototype RFID sensors to wirelessly measure temperature at the minimum distance of 10 meters and temperature measurement resolution of 1°C.
2. **Milestone 3.3 (M24):** Fully functional sensor system with temperature resolution of 0.25°C and humidity resolution of 1% at an interrogation distance of 10 meters.
3. **Milestone 5.4 (M36):** Test the developed sensing technology in a simulated building control environment and publish the test report.

Budget:

Total Project $ to Date:

- DOE: $375,092, Cost Share: $64,028

Total Project $:

- DOE: $1,399,998, Cost Share: $188,297

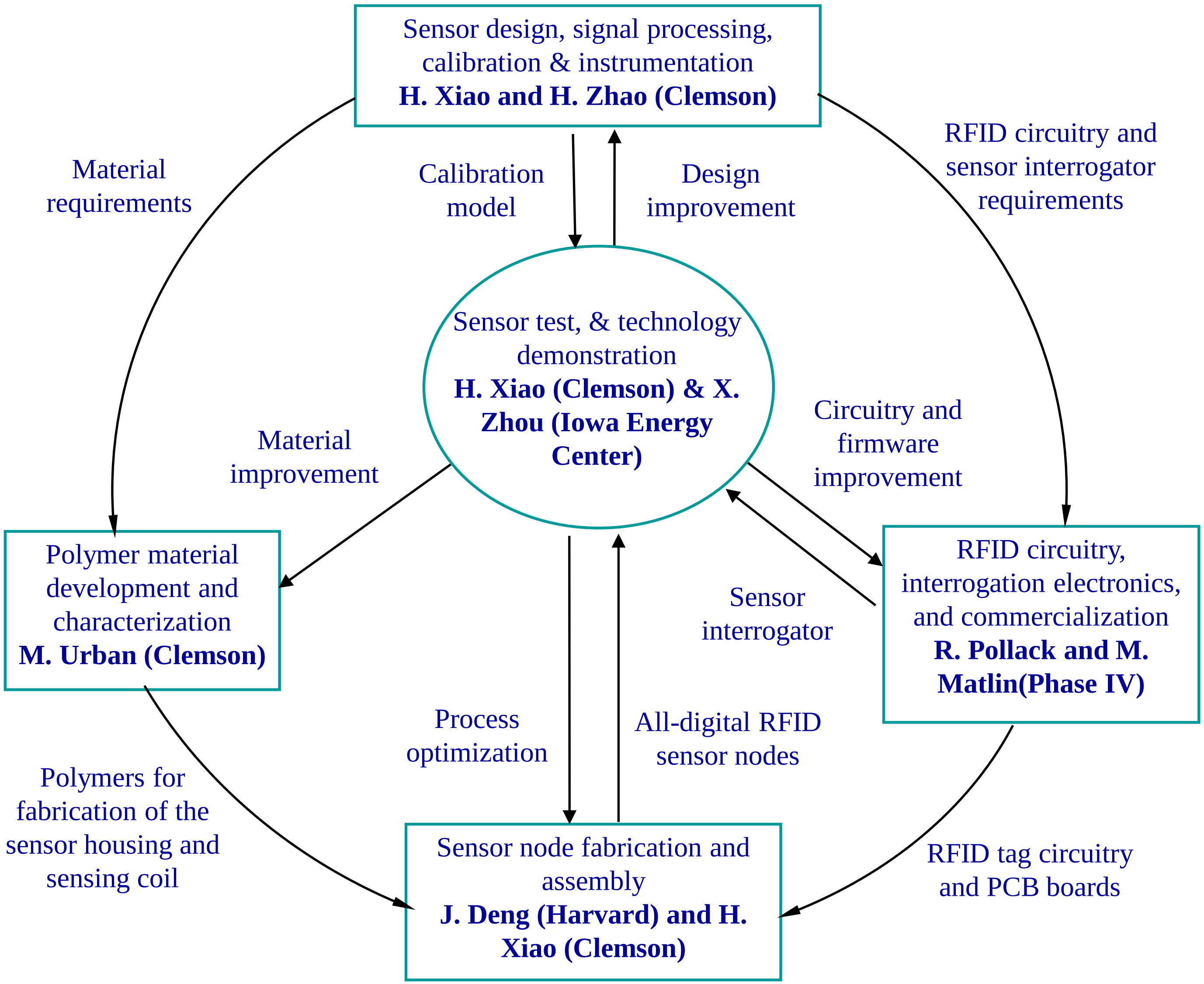
Key Partners:

Harvard University
Phase IV Engineering Inc.
Iowa Energy Center

Project Outcome:

In BP1, we have proved the all-digital concept by designing, fabricating, and testing functional RFID temperature sensor prototypes at 10-meter read distance and 1°C resolution.

Team



Combined skills in

- Sensors
- materials
- modeling simulation
- microfabrication
- electronics
- embedded systems
- Building control and management

Challenge

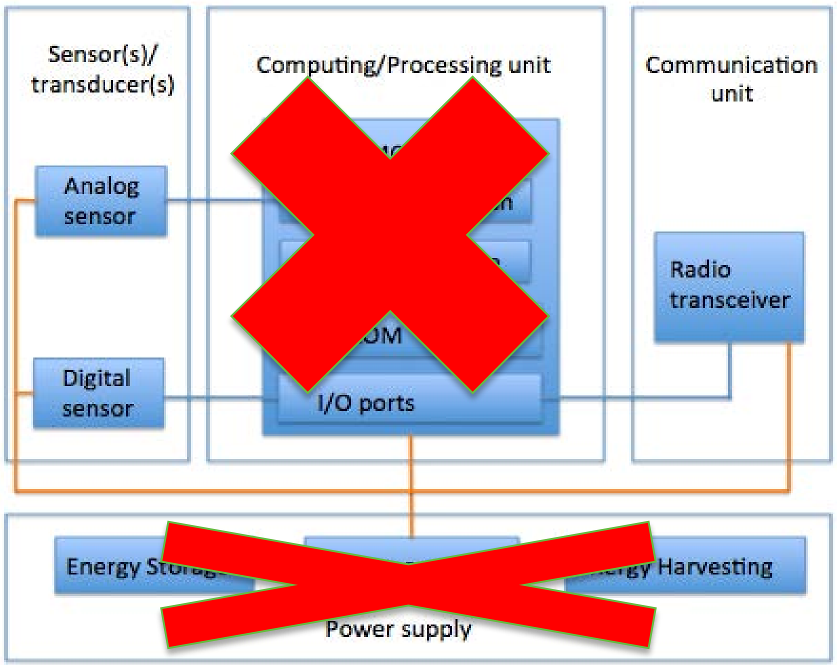
Problems:

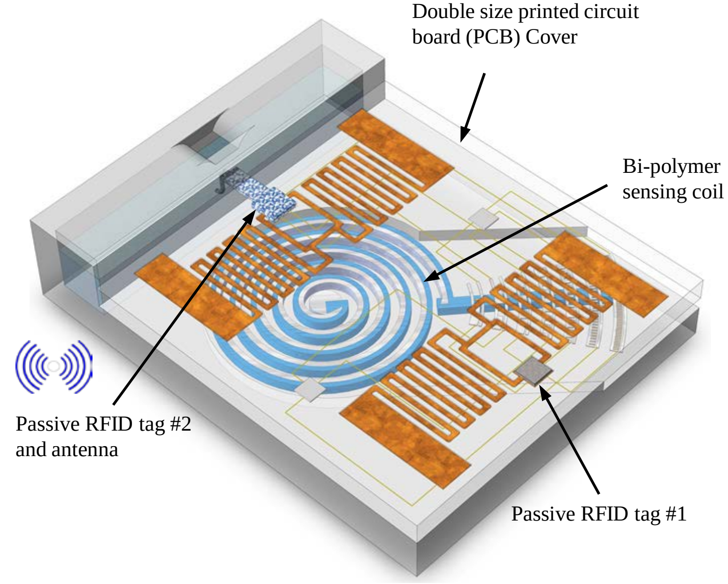
- More widespread use of sensors helps identify and detect faults in building operations which currently account for 0.3-1.8 quads of energy waste each year in the U.S. in the commercial sector alone.
- Sensors are preferred to be **non-intrusive**, **wireless**, **low power**, **easy to install, long lifespan**, and **convenient for the retrofit** of the old buildings.
- Existing wireless sensors are costly ($100/node) and require frequent maintenance because they
  - Need on-node processing
  - Need on-node battery (large power consumption short battery lifetimes, high maintenance)

Is it possible (?) to have a sensor that is

- **Power/battery free?**
- **Signal processing free?**

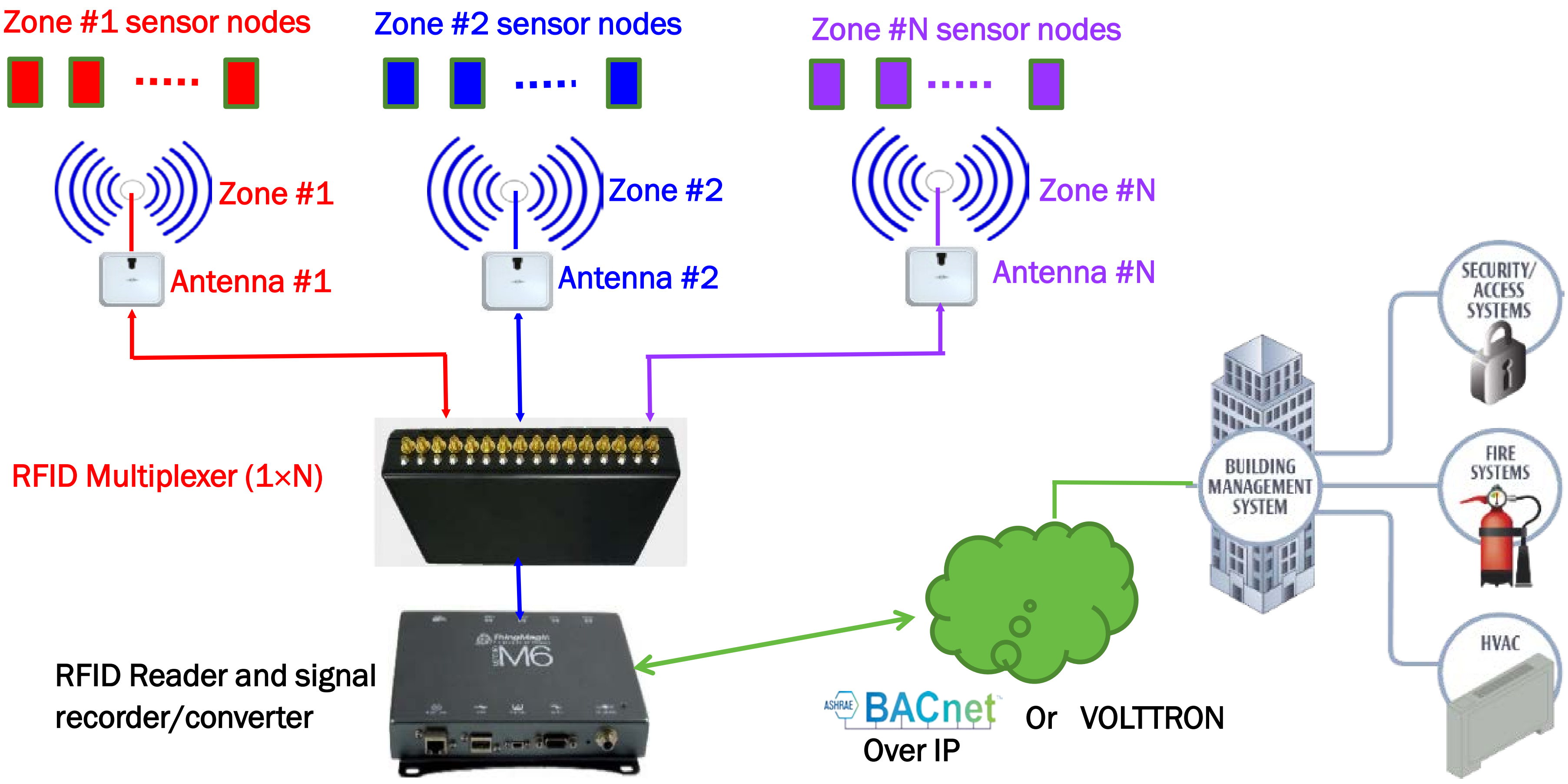
Approach – the all-digital passive RFID sensors





- **All digital: built-in digitizer with direct On/Off (1/0) outputs**
  - No on-node signal processing necessary
  - No on-node power supply (battery) needed
- **Passive RFID tags for ID and wireless communication**
  - Wireless interrogation
  - Plug & play operation
  - Networking and integration into BMS (BACnet or VOLTTRON)

Approach – integration with BMS

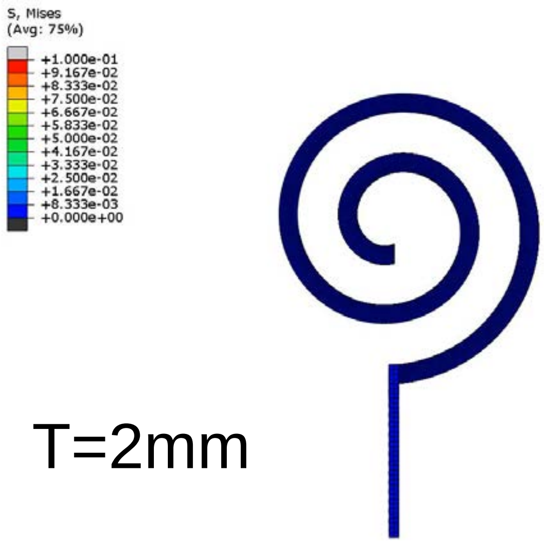


Impact

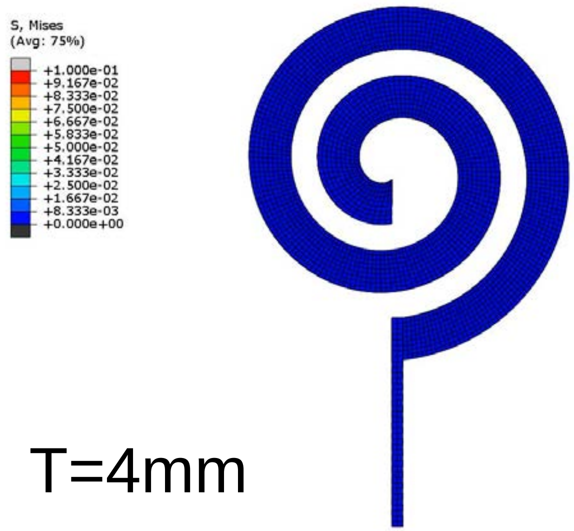
- **The all-digital RFID sensing technology advances the state-of-the-art to offer the following unique features**
  - Cost reduction by eliminating the needs for on-node signal processing and power supply
  - Maintenance-free because no battery is needed
  - Easy installation because of wireless operation
  - Plug & play and easy networking warranted by the digital ID of the sensor
  - The new concept can be adopted for sensing other parameters to offer the long desired sensing solution to "internet of things (IoT)".

- **Successful development and demonstration of the all-digital sensor prototype will help enable the BTO goals for multi-functional wireless sensor networks and energy savings of 17% for HVAC and 35% for lighting by 2030.**

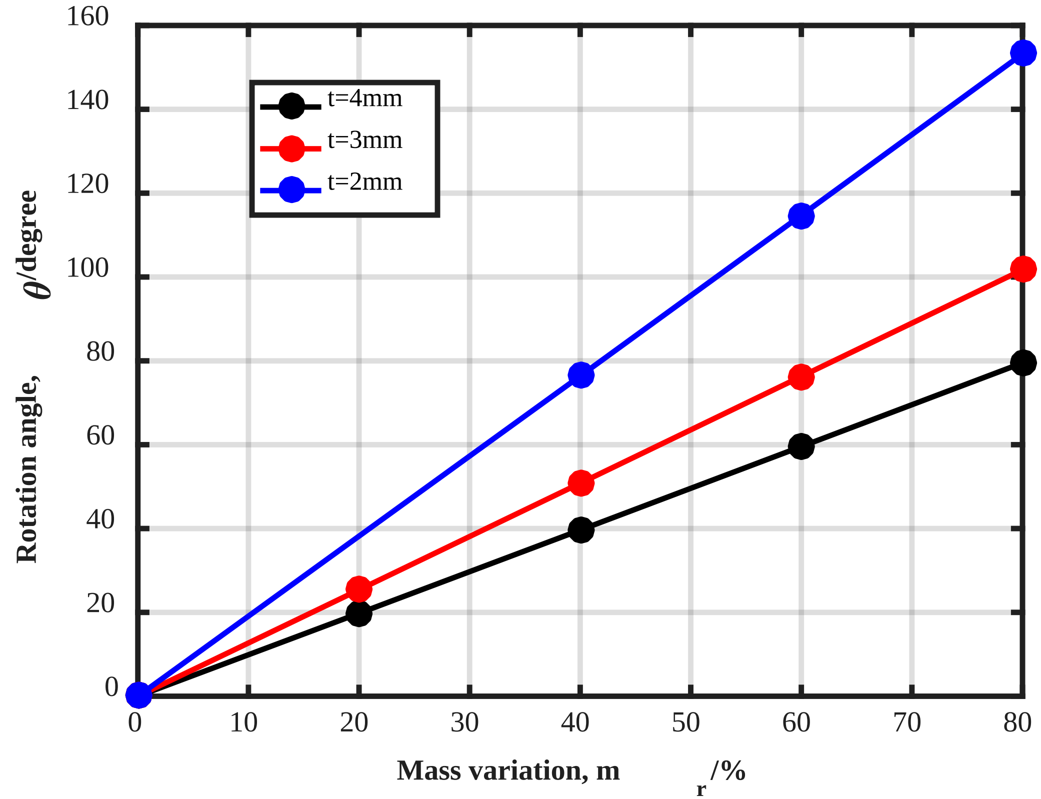
Progress – sensor design by modeling



T=2mm



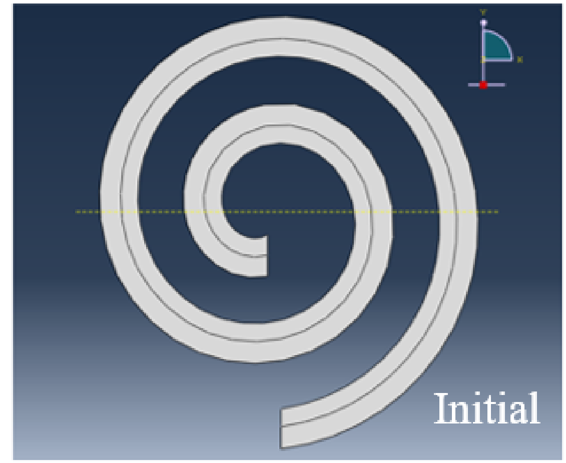
T=4mm

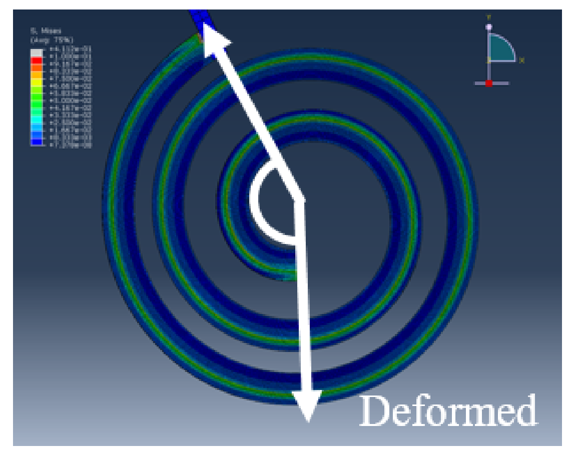


With 2-round Archimedean spiral coil as example, the thinner the coil, the larger the rotation angle.

Progress – initial sensor design parameters

	Material/Geometry Variables	Preliminary Design Parameter	Design Space
Coil Geometry	Dimension	3cm×3cm	2 - 4cm^2
	Total thickness	2mm	1 - 3mm
	Round number	2	1 - 4
	Rotation angle (dT=80°C)	151°	50° - 150°
	Thickness ratio (t_1/t_2)	0.2	Depends on E_1/E_2
Material Properties	Young's Modulus Ratio (E_1/E_2)	0.2 (E_1=1MPa, E_2=5MPa.)	Depends on material input
	CTE/CME difference ($\alpha_2 - \alpha_1$)	344ppm/°C	As large as possible
	Poisson's ratio	0.33	Not important



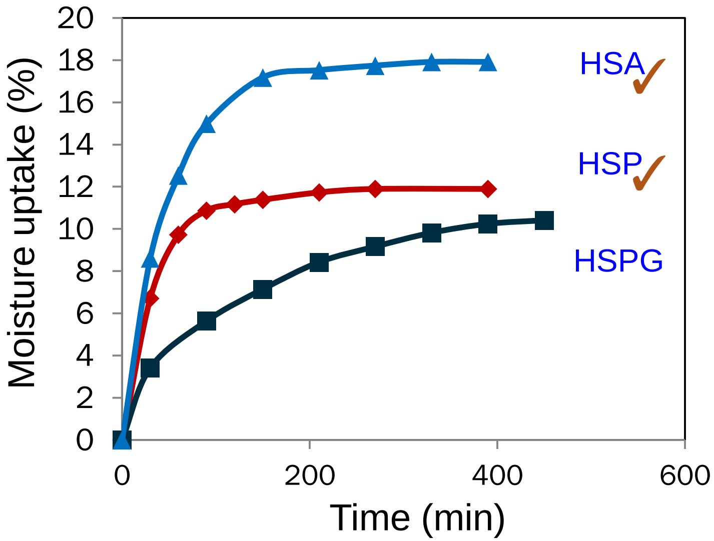


Progress – sensor materials

Polymers studied for moisture sensing

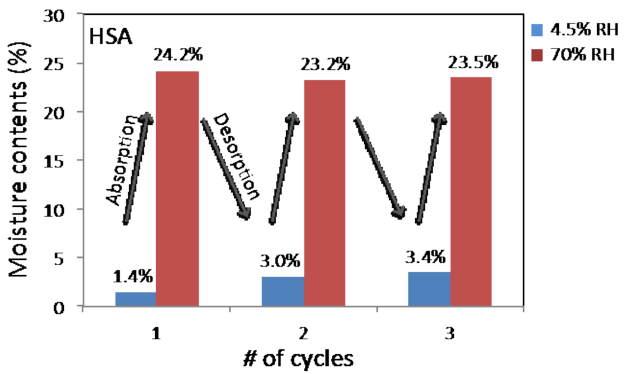
Polymer	Moisture content at 50% RH (w/w%)	
Amine-containing acrylic copolymer 1 (thermoplastic)	0.66	
Amine-containing acrylic copolymer 2 (thermoplastic)	0.62	
Polyether-Polyurethane 1 (thermoset)	1.06	
Polyether-Polyurethane 2 (double network)	0.78	
Hydroxyl-containing polymer 1 (HSP)	5.23	✓
Hydroxyl-containing polymer 2 (HSPG)	5.68	✓
Hydroxyl-containing polymer 3 (HSA)	14	✓

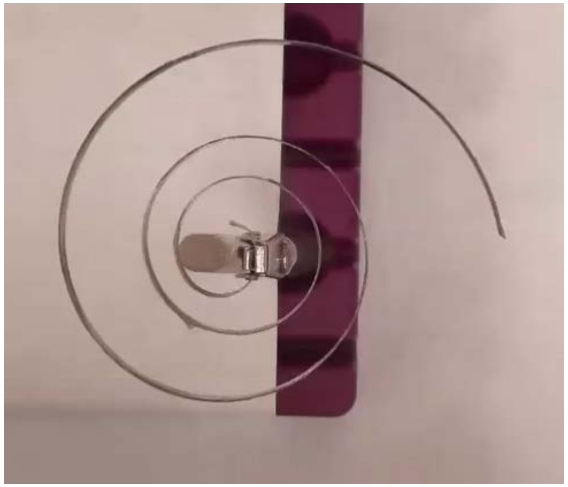
Polymer film thickness 0.045±0.005
RH increased from 4.5% to 69%, RT



Materials studied for substrate

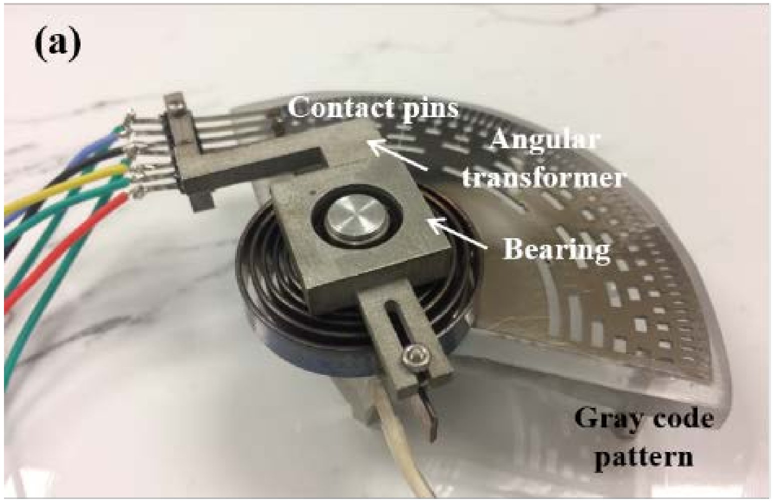
- Stainless steel ✓
- Silicone polymer

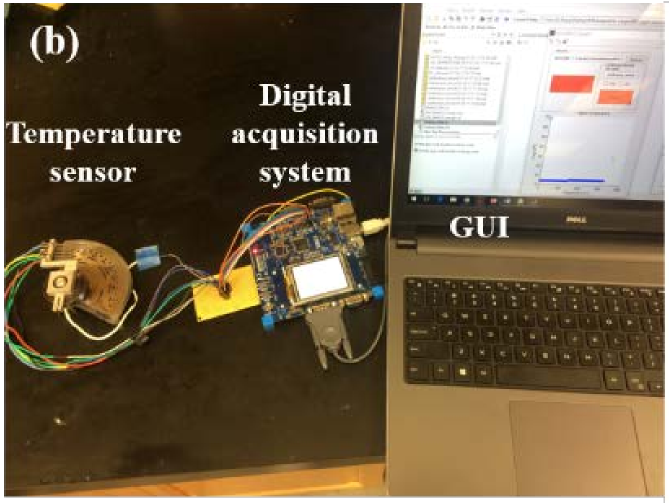


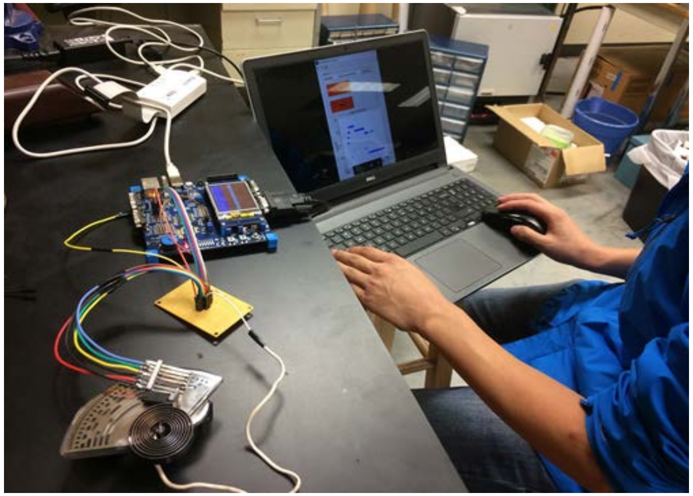


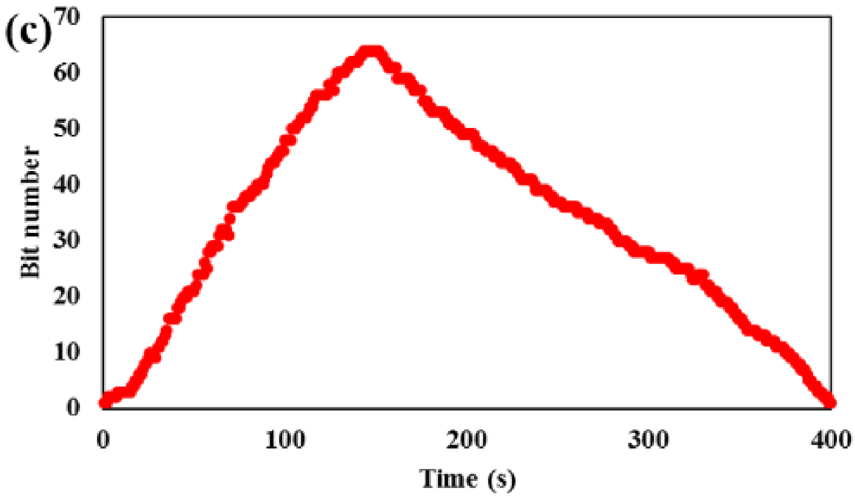
Progress – sensor structure and coding

- Common plane + Gary code + center shaft = Error free

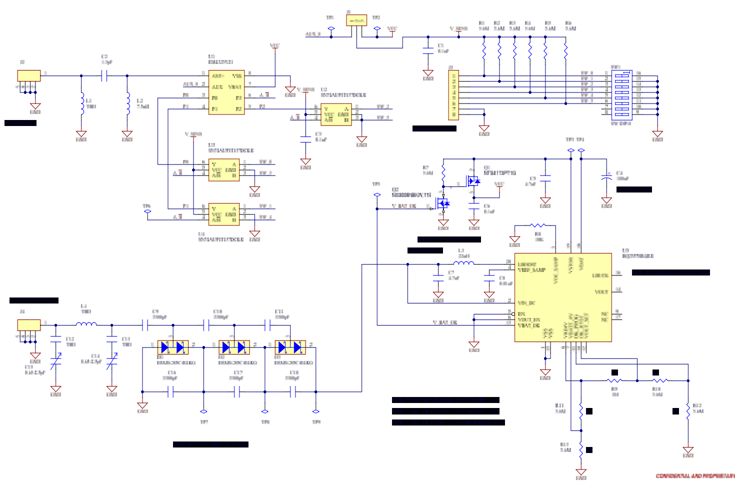


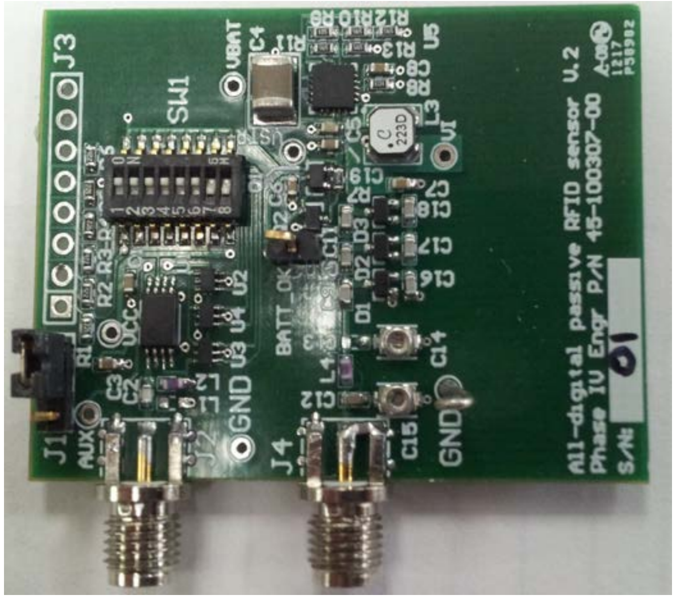


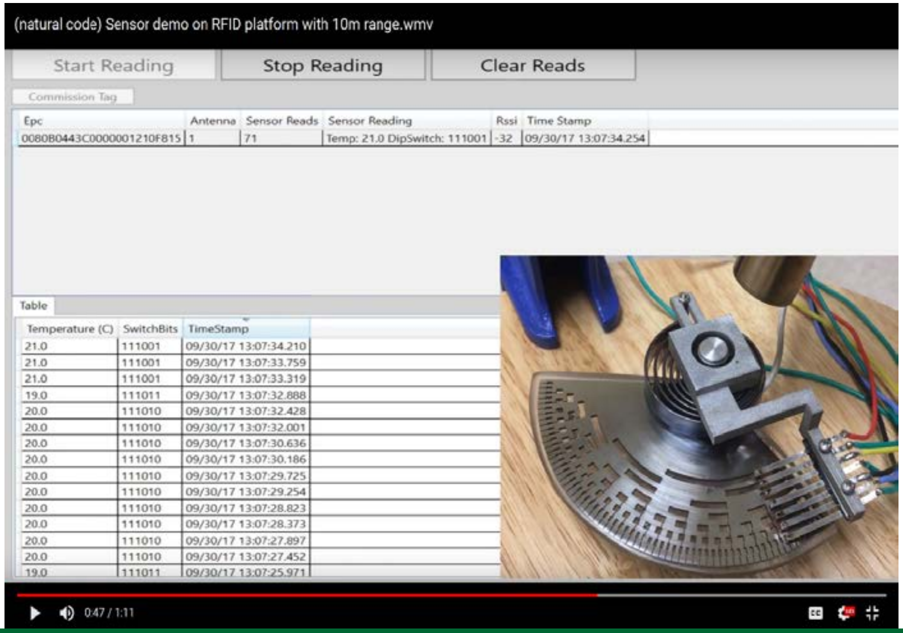




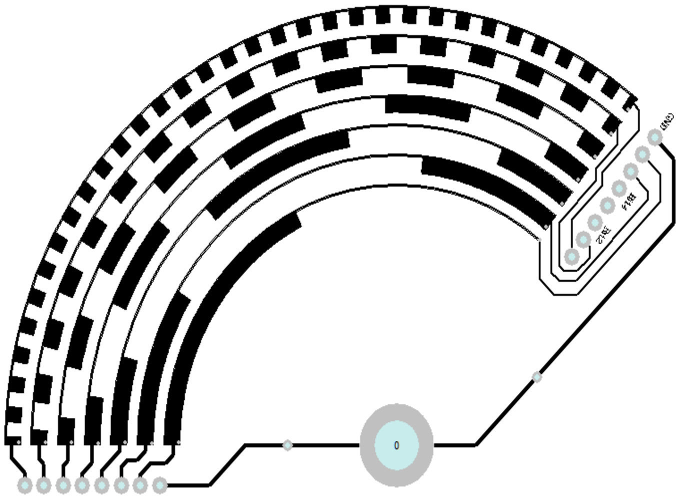
Progress – circuit, reader and software

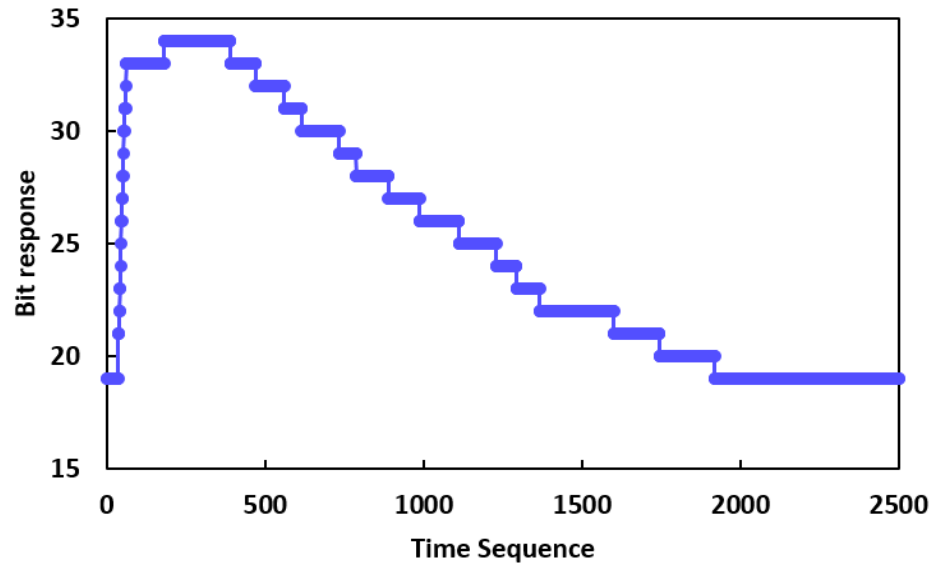


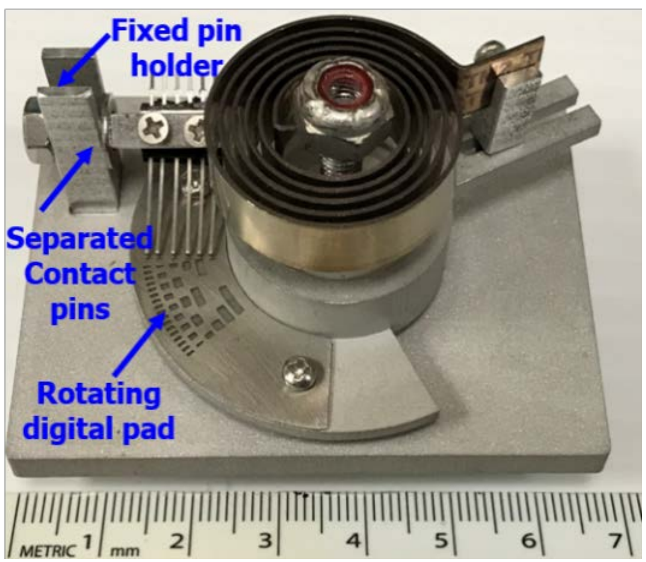


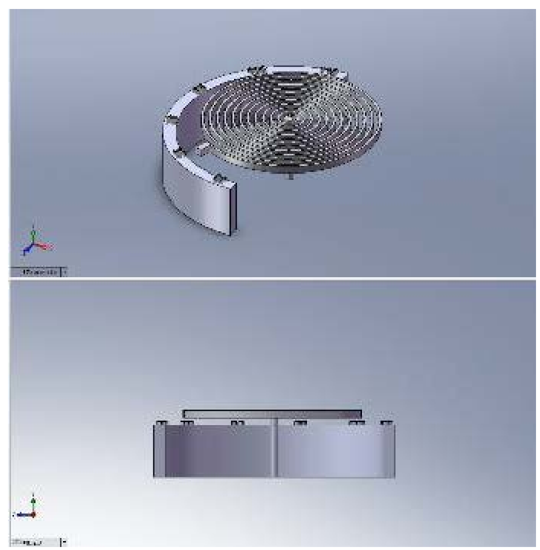


Progress – sensor fabrication and prototype

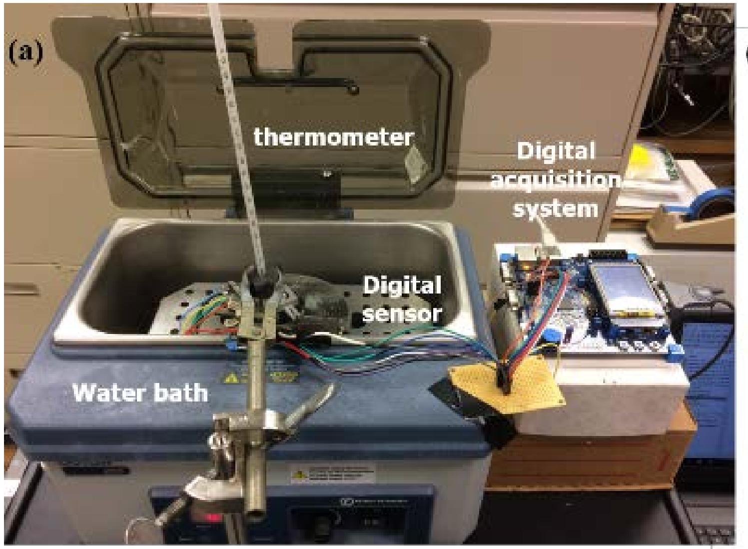




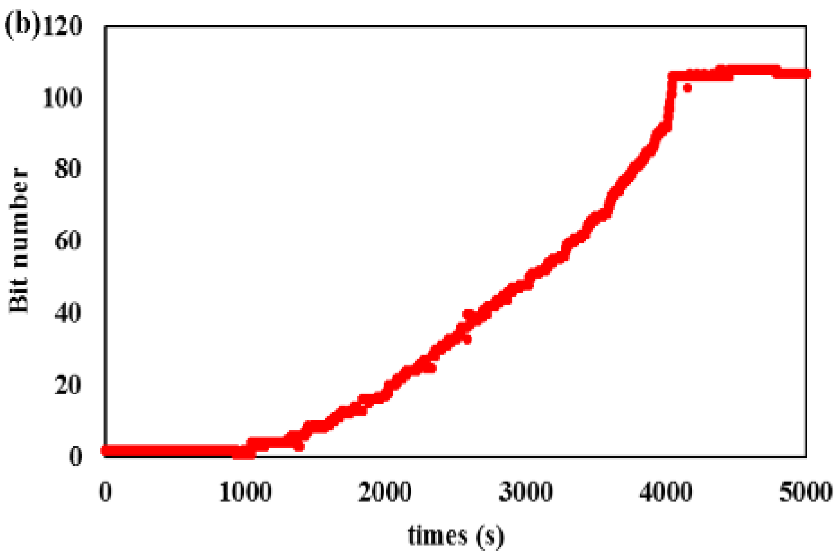


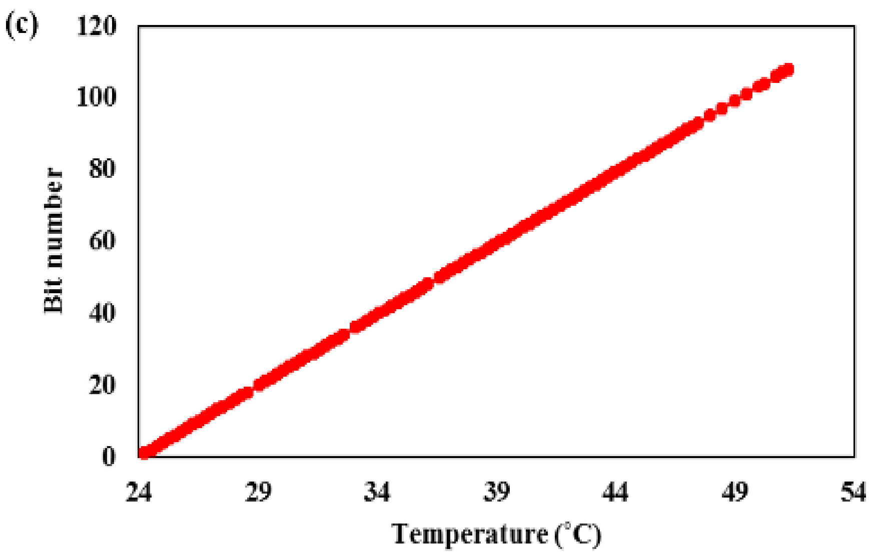


Progress – prototype sensor testing and results



- Error-free digital outputs
- Response time <1s
- Linear response
- Resolution of 0.1°C
- Repeatable

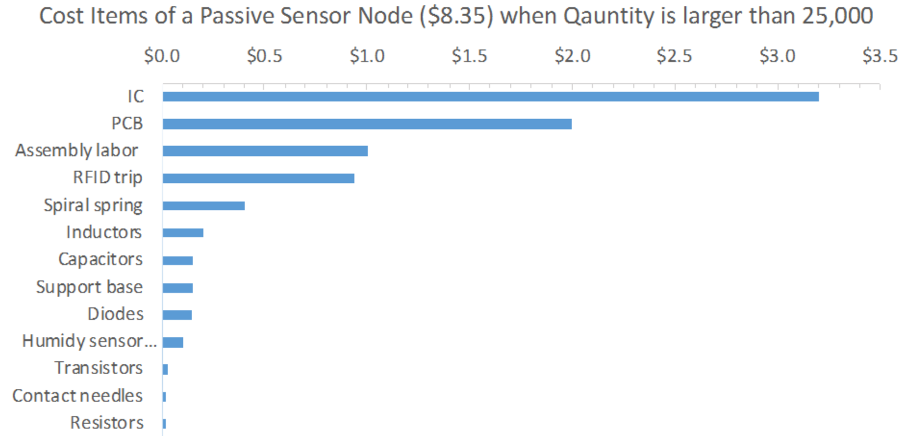




Progress – demonstration

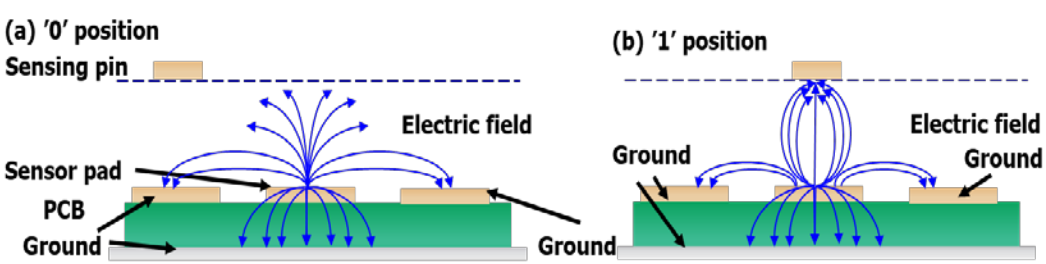
Stakeholder Engagement

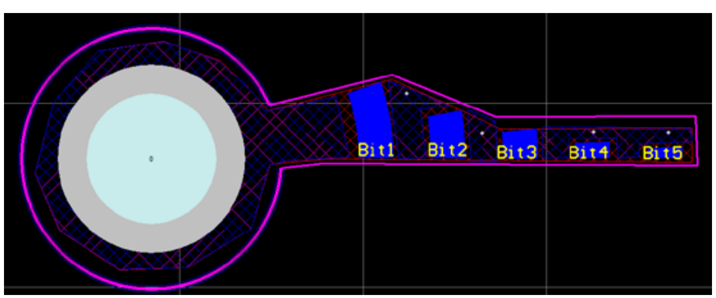
- Full participation of the all partners:
  - Bi-weekly project meetings to update technical progresses, coordinate work plan and solve project management issues.
  - On-going commercialization efforts through the PIs' institutions, led by
    - Mr. Andy Bluvas, Technology Commercialization Officer, Clemson University
    - Mr. Richard Pollack, Founder and CTO, Phase IV Engineering Inc.
  - Field demonstration planned at various stages
    - The Photonics Technology Laboratory at Clemson (BP2)
    - The Watt Family Innovation Center at Clemson (BACnet) (BP2)
    - Potentially at the FLEXLAB, Lawrence Berkeley National Laboratory (BP3)

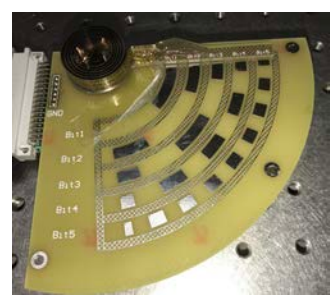


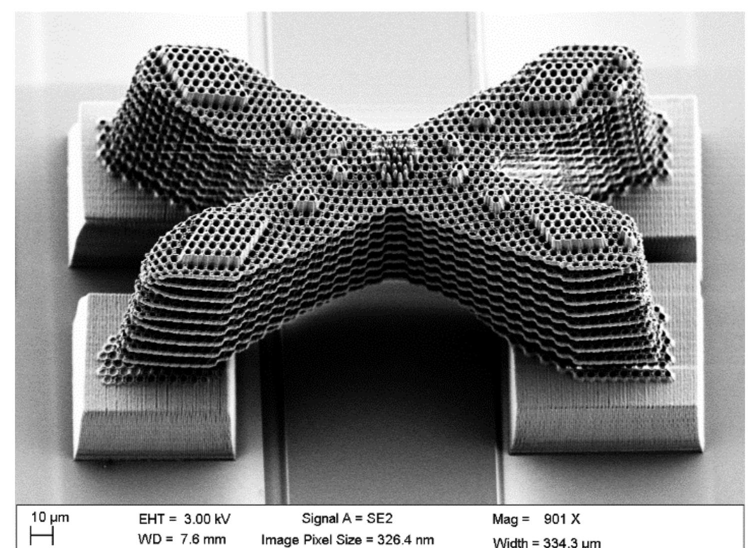
Remaining Project Work

- Technology development (BP2)
  - Temperature sensing has been fully demonstrated, will work on humidity sensors
  - Study the reading distance when interferences (blocking objects) are presented
  - Maximize the reading range by optimizing the hardware and software
  - Fabrication of low cost sensors using MEMS technology
  - Noncontact reading by self-capacitance









Remaining Project Work

- **Testing and demonstration**
  - Validate the system performance through comprehensive laboratory tests (BP2)
  - Develop the initial test plan (BP2)
  - Integrate the sensing system with the BACnet system (BP3)
  - Integration of the sensors with BMS (BP3)
  - Test the sensors and systems (BP3)
- **T2M - Commercialization**
  - Market discovery (BP2)
  - Cost performance model (BP2)
  - Production level cost model (BP2)
  - Next stage partner and funding (BP3)

Thank You

Clemson University

Hai Xiao, Professor

864-656-1295, haix@clemson.edu

REFERENCE SLIDES

Project Budget

Budget History					
10/01/2016 – 12/31/2017 (past)		FY 2018 (current)		FY 2019 – 12/31/2019 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$375,092	$64,028	$576,662	$61,490	$448,244	$62,779

Project Plan and Schedule

Project Schedule														
Project Start: 10/01/2016		Completed Work												
Projected End: 12/31/2019		Active Task (in progress work)												
		Milestone/Deliverable (Originally Planned)												
		Milestone/Deliverable (Actual)												
	FY2017				FY2018				FY2019				FY 2020	
Task	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	
Past Work														
MS 1.1: IP Management Plan (Q1)														
MS 2.1 Requirements specifications documented (Q3)														
MS 2.2 Initial sensor designs (Q2).														
MS 1.2.1: Determine resource as the T2M lead (Q3)														
MS 2.3 Polymers are identified for humidity sensor (Q3)														
MS 2.5 Read the RFID ports at a distance of 7m (Q3)														
MS1.2.2: T2M Draft Plan (Q4)														
MS 1.3: Preliminary cost-performance model (Q4)														
MS 2.4 Procedures for sensor fabrication (Q4)														
MS 2.6 Prototype sensors read at 10 m and 1°C (Q4)														
Current/Future Work														
MS 3.1 Improved structural and geometric designs (Q6)	Q6													
MS 4.1 Report on Market discovery efforts (Q6)	Q6													
MS 4.2 Cost performance model completed (Q7)	Q7													
MS 3.2 Optimized polymer formulations (Q8)	Q8													
MS 3.3 RFID Tags interrogated at a distance of 10 m (Q8)	Q8													
MS 3.4 Fully functional sensor system (Q9)	Q9													
MS 3.5 Initial test plan (Q9)	Q9													
MS 5.2 Test plan is finalized (Q10)	Q10													
MS 7.1 Present a post-project financing and transition plan (Q10)	Q10													
MS 5.1 Sensor nodes registered to BMS (Q11)	Q11													
MS 7.2 Develop pitch deck to engage next-stage partners (Q11)	Q11													
MS 6.1 Demo hardware and software tested and passed (Q12)	Q12													
MS 7.3 Identify next stage partners and funding (Q12)	Q12													
MS 6.2 Test report completed and ready for publication (Q13)	Q13													
MS 7.4 Final report on transition (Q13)	Q13													