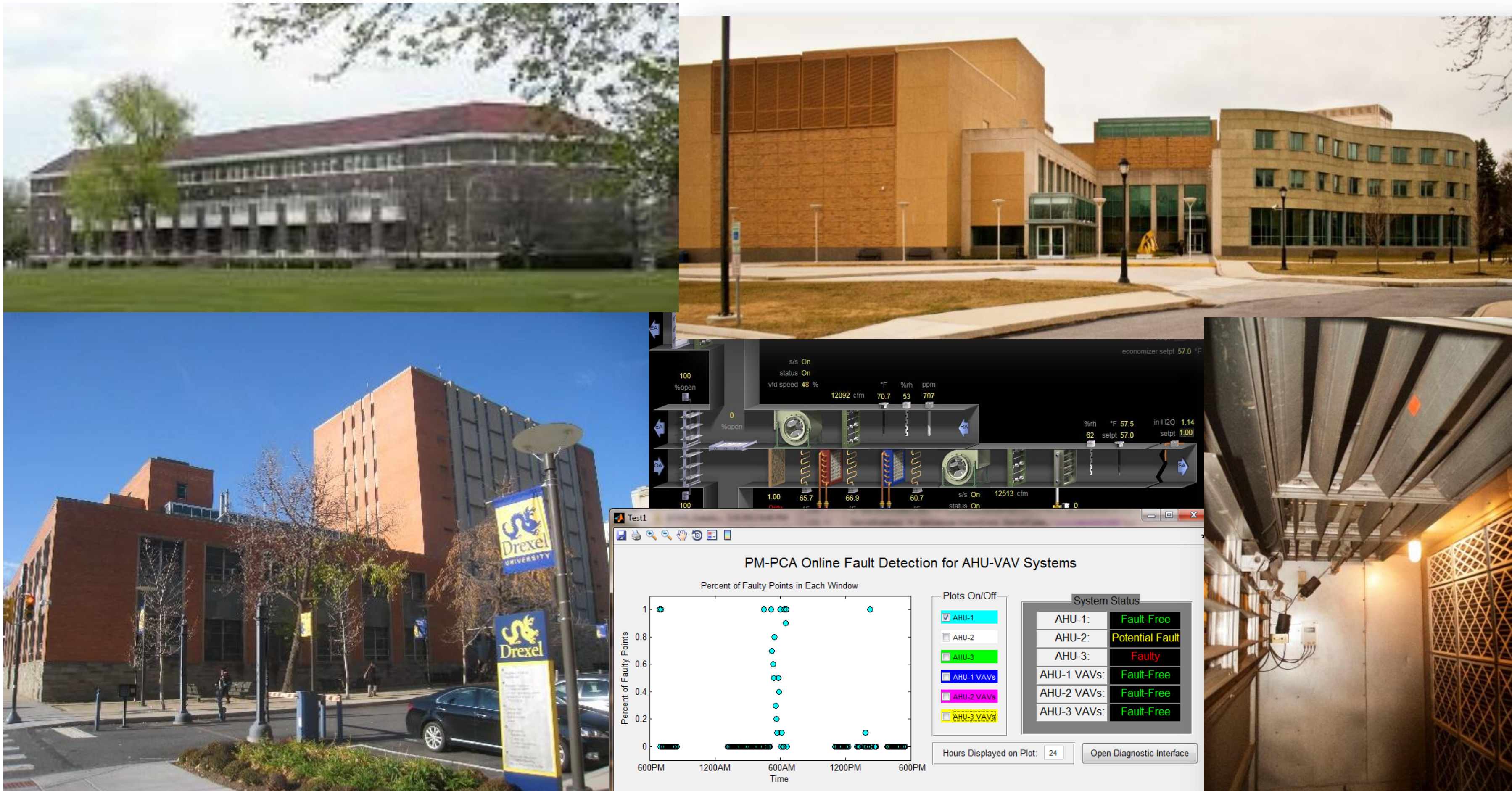
CBEI: VOLTTRON Compatible and Cost-effective Fault Diagnostic Solutions for AHU-VAV and AHU-CAV Systems

2015 Building Technologies Office Peer Review



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Project Summary

Timeline:

Start date: May 1st 2014

Planned end date: April 30th 2016

Key Milestones

1. Identify one or more industrial partners; 10/30/14
2. Develop fault diagnosis solutions that effectively diagnose faults in demo buildings and are a VOLTTRON agent; 2/28/15

Target Market/Audience:

Buildings: small and medium sized commercial buildings (SMSCB)

Audience: control company, service company, fault diagnosis company

Key Partners:

CBEI-Drexel University
Pacific Northwest National Laboratory

Budget:

Total DOE $ to date: $322,858

Total future DOE $: $300,000

Project Goal:

Develop and demonstrate cost-effective and VOLTTRON-compatible automated fault detection and diagnosis strategies for *Air Handling Unit (AHU) Variable Air Volume / Constant Air Volume (VAV/CAV)* systems that are typically used in SMSCBs with the potential to save at least 10-30% HVAC system energy, 2-3 years payback time and will require no additional operator training

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CONSORTIUM for BUILDING ENERGY INNOVATION

Vision:

By 2030, deep energy retrofits that reduce energy use by 50% in existing SMSCB, which are less than 250,000 sq ft

Mission:

Develop, demonstrate and deploy technology systems and market pathways that permit early progress (20-30% energy use reductions) in Small and Medium Sized Commercial Buildings

Our Goals:

- **Enable deep energy retrofits** in small to medium sized commercial buildings
- **Demonstrate energy efficient systems** tailored for SMSCBs in occupied buildings – living labs
- **Develop effective market pathways** for energy efficiency with utilities and other commercial stakeholders: brokers, finance, service providers.
- **Provide analytical tools** to link state and local policies with utility efficiency programs

CBEI Partners

Industry
- Bayer MaterialScience
- United Technologies Research Center

Economic Development Organizations
- DVIRC
- PIDC – Driving growth to every corner of Philadelphia
- Ben Franklin Technology PArtners

Universities
- PennState
- NJIT
- Penn – University of Pennsylvania
- Drexel University
- Carnegie Mellon University
- VirginiaTech – Invent the Future
- Purdue University
- Morgan State University
- Rutgers

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Purpose and Objectives - Problem Statement

- AHU-VAV systems have strong energy and indoor air quality impacts
- Serve nearly <u>19%</u> of small- and medium- sized commercial building floor area
- Faults are commonly observed in AHU-VAV systems

<u>AHU and market-driven challenges:</u>

- Nonlinear systems with multiple operational modes
- Custom, "built-up" systems
- Lack of sensors and measurement quality
- Lack of willingness to invest in automated fault detection and diagnosis (AFDD)
- Engineering costs for customization of rules/thresholds
- Low tolerance for false alarms
- Requires a non-intrusive strategy that will not impact:
  - Control strategies
  - Comfort

Picture from www.iowaenergycenter.org/

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Purpose and Objectives

Target Market and Audience: Market – commercial buildings that use AHU systems (19% small and medium sized commercial building floor area and 20% - 30% primary energy consumption of total commercial building sector); Audience – control company, service company, and fault diagnosis company

Impact of Project:

1. Products: A suite of fault detection, fault diagnosis, and fault impact estimation strategies that can be developed to be integrated or stand-alone software products for AHU-VAV systems
2. Impact path:
   - Near-term
     - Developed strategies are further demonstrated and developed for market adoption
     - Industrial partners identified
   - Intermediate-term
     - Developed into market ready products and implemented in 5-10 buildings
   - Long-term
     - Products are implemented in more than 50 buildings and are showing substantial energy savings

Approach

Overall Approach

Develop cost effective AHU AFDD solutions

- Using integrated data-driven and rule-based methods
- Including energy impact estimation
- Automated for rapid, low-cost deployment

Demonstrate the solutions in a variety of small to medium sized commercial buildings

Develop solutions to be VOLTTRON agent

- Reduced computational requirements
- Demonstrate automation and interoperable, open-source deployment

Identify commercialization partners and work closely with the partners to ensure an accelerated technology transfer

Key Issues

Need to have minimum upfront cost (engineering hours and additional measurements)

AHUs are mostly "built-up" (custom) one-of-a-kind systems

- Needs to automatically adapt to a wide variety of system configurations and control/operation strategies

Multiple operational modes and continuously transient operation

- Distinguishing weather/operational-mode system impacts and faulty operation has been challenging

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Approach

Distinctive Characteristics

Plug-and-play implementation

- Minimal upfront engineering costs (no modeling/customization requirements)
- No requirement for faulty/specialized training data
- Automatically "learns" system operational characteristics

Adapts to any building's existing sensor set and configuration

De-couples detection and diagnostic algorithms

- Reduced computational requirements
- Cross-validation of results

Demonstrated to be effective for all types of faults

- Dampers, valves, fans, sensors, controls, etc.

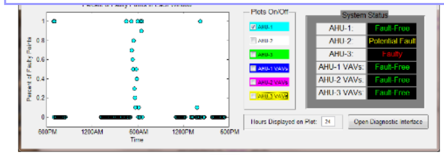
It is mostly a "Passive" method (no intrusive testing) but allows active diagnosis to be used if users choose to

AHU Diagnosis Method overview

AHU

Operational data from a AHU

PM-PCA Fault Detection



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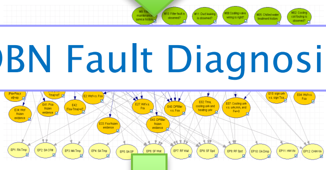


DBN Fault Diagnosis

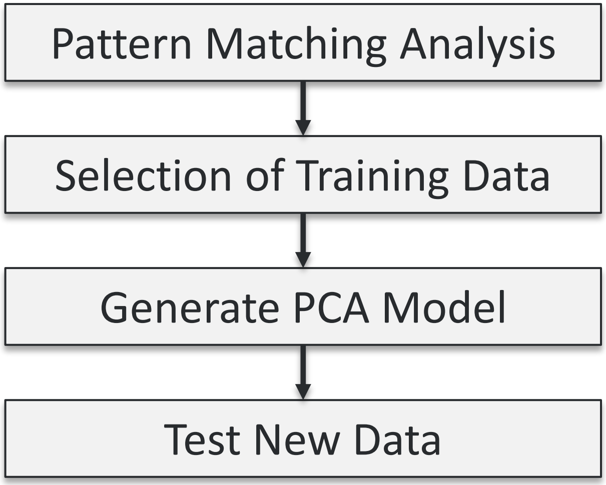
PNNL Active Diagnosis

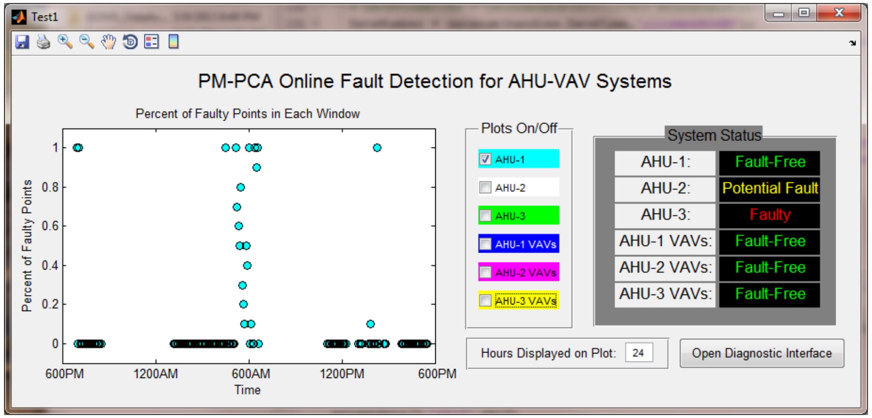
Energy Impact Analysis

Approach – AHU fault detection method

Pattern Matching Principle Component Analysis (PM-PCA)

1. Use pattern matching techniques to identify historical data under similar operational conditions.
   - Same mode of operation under similar internal and external loads
   - Overcomes the intrinsic obstacles previously discussed
   - Utilizes two complementary pattern matching algorithms for robustness
2. Generate a PCA model using the historical data identified in the previous step
3. Apply this PCA model to the current “test” data
4. Determine whether the test data is operating in a *normal* or *faulty* condition
   - Squared prediction error (Q-residual)





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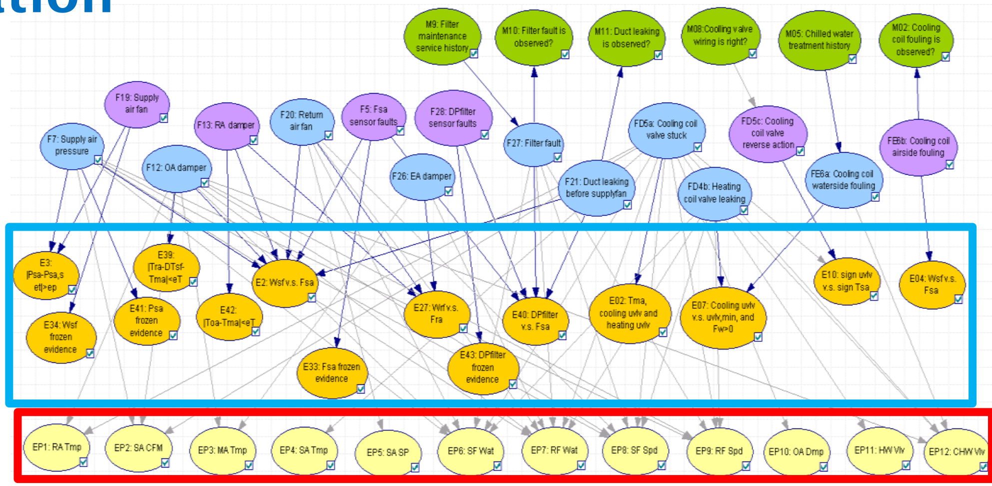
Approach – AHU fault diagnosis method

Bayesian network for fault isolation

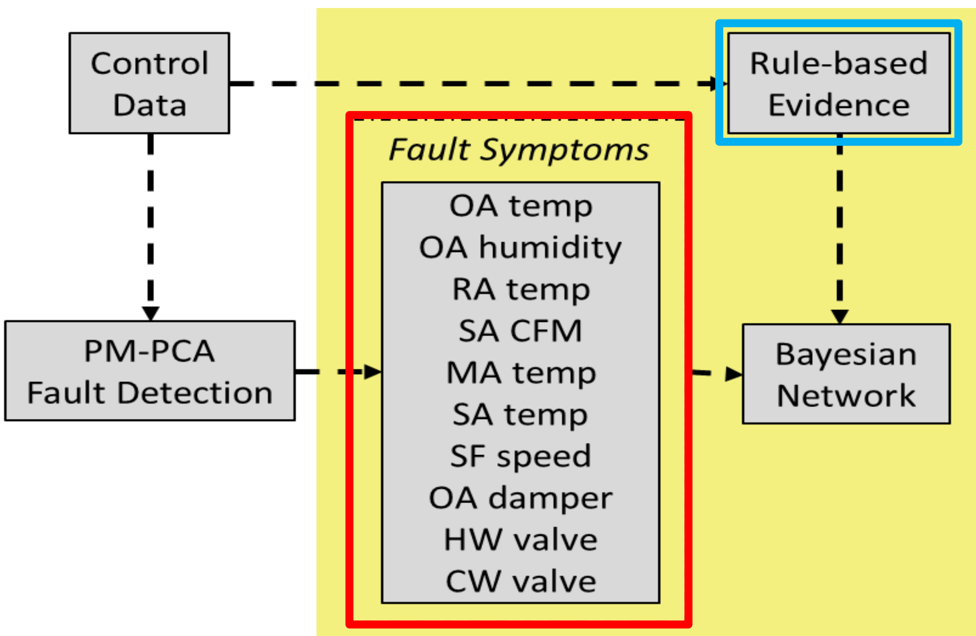
No faulty data training needed!



- Information from the fault detection algorithm is passed to the diagnostic Bayesian network
- This information is combined with rule-based evidence in the Bayesian network
  - Thresholds for all rule-based evidence are automatically learned from training data

Example: Fan stuck at low speed

- Rule-based evidence
  - Supply air pressure set-point is not being met
- Could be a fan fault or a sensor fault
- Pattern-matching evidence
  - Supply air pressure is low
  - Fan power is low
- Results in the diagnosis "*fan stuck at fixed speed, too low*"



Progress and Accomplishments

Demonstration Projects

- Implement AFDD package for continuous monitoring at 3-4 buildings
- Additionally, experiments will be conducted where faults are artificially injected into the buildings to demonstrate the AFDD package and improve robustness

Building 101 at the Navy Yard (Philadelphia, PA)

- Three story, 55,000 ft^2 commercial building
- 3 AHUs, 26 VAV-boxes
- DX cooling, boiler heating

Iowa Energy Center (Ankeny, IA)

- One story, < 10,000 ft^2 commercial
- 2 AHUs, 8 VAV-boxes
- Chiller cooling, boiler heating

… Building (West Chester, PA)

- Three story, 90,000 ft^2 music school building
- 7 AHUs, 98 VAV-boxes
- Chiller cooling, boiler heating

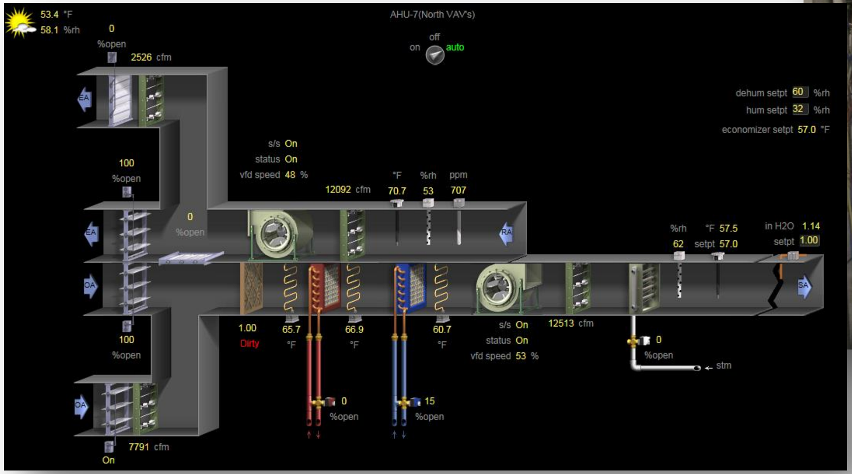
Stratton Hall (Philadelph…

- Four story, 74,000 ft^2 psychology school buil…
- 3 AHUs, 54 VAV-boxes
- Chiller cooling, steam heating

Progress and Accomplishments

Typical Fault Injection Experiments at Demonstration Buildings (during heating, cooling and economizer modes)

- Outdoor air damper stuck
- Chilled water valve stuck
- Hot water valve (including reheat) stuck
- Supply air temperature sensor positive and negative biases
- Supply air static pressure sensor bias
- Mixed air temperature sensor positive bias and frozen
- Supply fan stuck
- Unstable economizer control
- CO2 sensor frozen



Progress and Accomplishments – fault detection method

Results: PM-PCA Fault Detection Method

- All faults with symptoms are detected at all demonstration buildings with nearly no false positive alarms
- Undetected faults are those that do not have significant impact on the system

Sample Results of Fall/Winter Demonstration in Swope Building

Date	Description	Severity	Accurately Detected	False Alarm	Fault-Free	Missed Detection	Comments
2014-09-29	Fault Free	n/a			Fault-Free		
2014-09-30	Fault Free	n/a			Fault-Free		
2014-12-15	Fault Free	n/a			Fault-Free		
2014-12-20	Fault Free	n/a			Fault-Free		
2014-12-21	Fault Free	n/a			Fault-Free		
2014-12-24	Fault Free	n/a			Fault-Free		
2014-12-28	Fault Free	n/a			Fault-Free		
2014-09-29	OA damper override	100% open	Detected				
2014-09-29	HW valve override	40% open	Detected				
2014-09-30	SAT setpt mod	-5F	Detected				
2014-09-30	CW valve override	50% open	Detected				
2014-10-01	SA SP stpt mod	-0.3 in. H20	Detected				
2014-12-15	MA temp. sensor bias	negative 6°F	Detected				
2014-12-16	OA damper stuck	stuck at 0%	Detected				
2014-12-16	OA damper stuck	fixed at 20%	Detected				
2014-12-17	RF stuck	fixed at 40%	Detected				
2014-12-17	MA temp. sensor frozen	frozen at 58F				Missed	Minimal impact, no symptoms
2014-12-18	MA temp. sensor bias	positive 5F	Detected				
2014-12-18	SF stuck	fixed at 45%				Missed	No impact, no symptoms
2014-12-20	PH coil vlv locked	locked at 10%	Detected				
2014-12-21	MAT sensor bias	negative 5F				Missed	Some impact, minimal symptoms
2014-12-22	SAT sensor frozen	stuck at 55F				Missed	No impact, no symptoms
2014-12-24	Unstable Economizer	P = 4	Detected				
2014-12-27	OA damper stuck	stuck at 40%	Detected				
2014-12-28	SA SP sensor bias	+0.5 in. H20				Missed	Minimal impact, no symptoms
2014-12-29	CO2 sensor frozen	frozen at 1100 ppm				Missed	Minimal impact, no symptoms
2014-12-29	Unstable Economizer	P = 6				Missed	No impact, no symptoms
2015-01-03	HC Vlv Stuck	stuck at 15%	Detected				

Progress and Accomplishments – fault diagnosis method

Diagnostic Bayesian Network Method Results

Effectively diagnose all common types of faults:

- **Damper faults**
  - Stuck, leaking
- **Valve & coil faults**
  - Stuck, leaking, fouling
- **Fan faults**
  - Fixed speed, low eff.
- **Sensor faults**
  - Biased, stuck, failure
- **Control faults**
  - Instability

Coming Soon:

- Operator error faults

Easily adapts to a variety of different AHU configurations:

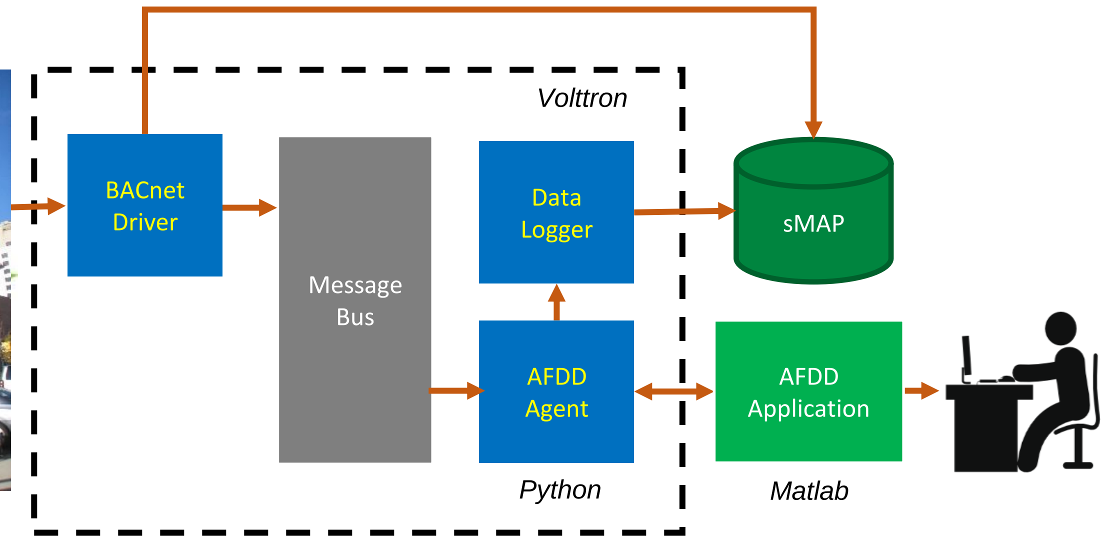
- **Building 101** – DX coil, no outdoor air mixing (no return air damper)
- **Swope Hall** – dedicated outdoor air system, humidification-based control
- **ASHRAE 1312** and **Stratton Hall** – traditional economizer and chilled water coil

Automatically customizes:

- Network architecture
- Conditional probability tables
- Thresholds/evidence-collection

Progress and Accomplishments – VOLTTRON Agent

- VOLTTRON, developed by PNNL, is a platform that enables distributed sensing and controls
- Developing our solutions to be a VOLTTRON agent will help reduce the middleware development needs and also enrich the agents that are VOLTTRON compatible



Drexel's Stratton Hall will be a live VOLTTRON and AHU FDD demo building

Progress and Accomplishments

Lessons Learned:
1) Automatic customization of a Bayesian network for a variety of system types (across all modes of operation) requires a dynamically re-configuring network architecture
2) Pattern-matching algorithm speed was improved by using some basic pre-processing during data archiving that allows for an “intelligent” rather than a comprehensive search for relevant historical data

Most important Accomplishments: About ten companies have expressed interests in our developed solutions. Three companies have committed to work closely in the coming months and to provide potential demonstration data

Market Impact:
– Literature indicates 30% energy waste due to faults for AHUs, which is 6-9% total commercial building energy consumption
– Data from demonstration buildings indicate that a single undetected AHU fault can result in over $1,600/month in additional utility costs without impacting occupant comfort

Awards:

Best Demo Award in the 1st Annual ACM BuildSys Conference on Embedded System for Energy-Efficient Buildings, November, 2014, Memphis, TN.

Project Integration and Collaboration

Project Integration:

- Bi-weekly meetings with partner organization (PNNL)
- Presentations to stakeholders (VOLTTRON workshop, ACM conference, and other workshops)

Partners, Subcontractors, and Collaborators:

PNNL, CSIRO (Australia – we performed a side-by-side comparison study between our two solutions)

Communications:

Regnier, A., J. Wen, J. Schwakoff, "Automated Diagnostics for AHU-VAV Systems using Pattern Matching", Proceedings of the 1st Annual ACM BuildSys Conference on Embedded System for Energy-Efficient Buildings, November, 2014, Memphis, TN.

Wen, J. and A. Regnier, "Building Operation Challenges and Opportunities: Automated Fault Detection and Diagnosis for AHU-VAV Systems," Invited Panel Speaker, 2014 Biennial Workshop in Service Engineering Energy-Aware Operations in Manufacturing and Service Enterprises, Philadelphia, PA, 2014.

Regnier, A. and J. Wen "AFDD for AHU-VAV Systems: Volttron Integration", CBEI Volttron Workshop, October 2014, Philadelphia, PA. http://cbei.psu.edu/portals/cbei/Resources/Presentations/20141021Voltron/6_2014-10-21_ Volttron_presentation_Rev1.pdf.

Next Steps and Future Plans

Next Steps and Future Plans: we will work closely with our market partners and PNNL team

- to enable the existing AHU-VAV/CAV diagnosis solutions to be a continuous commissioning tool, which include at least the following
  - developing a user interface that can effectively provide fault detection information for commissioning engineers
  - adapting the developed Pattern Matching Principle Component Analysis fault detection solution to detect faults from systems other than AHU-VAV/CAV systems, such as a chiller system
- to integrate the existing AHU-VAV/CAV diagnosis solutions into a cloud based diagnosis tool, which include developing at least the following functions:
  - being able to analyze offline data without any training data
  - active diagnosis functions for a wide range of AHU-VAV/CAV faults
  - capabilities to work with other cloud-based fault detection/diagnosis solutions provided by our market partner
- Identify 5-10 SMSCB buildings as demonstration buildings, demonstrate and document the cost-effectiveness of the AHU-VAV/CAV fault diagnosis solutions, together with the new functions/features, for at least two seasons

REFERENCE SLIDES

Project Budget

Project Budget: See table below
Variances: None
Cost to Date: $258,698
Additional Funding: None

Budget History					
CBEI BP3 (past) 2/1/2013 – 4/30/2014		CBEI BP4 (current) 5/1/2014 – 4/30/2015		CBEI BP5 (planned) 5/1/2015 – 4/30/2016	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$229,126	$0	$322,858	$0	$300,000	$0

CBEI – Consortium for Building Energy Innovation (formerly EEB Hub)
BP – Budget Period

Project Plan and Schedule

Project Schedule	
Project Start: 5/1/13	Completed Work
Projected End: 4/30/16	Active Task (in progress work)
	Milestone/Deliverable (Originally Planned) use for missed milestones
	Milestone/Deliverable (Actual) use when met on time

	BP3 (2013-14)				BP4 (2014-15)				CBEI BP5 (2015-16)			
Task	Q1 (Feb-Apr)	Q2 (May-Jul)	Q3 (Aug-Oct)	Q4 (Nov-Apr)	Q1 (May-Jul)	Q2 (Aug-Oct)	Q3 (Nov-Jan)	Q4 (Feb-Apr)	Q1 (May-Jul)	Q2 (Aug-Oct)	Q3 (Nov-Jan)	Q4 (Feb-Apr)
Past Work												
Q1 M1: Fault Injection Plan Complete												
Q2 M2: FDD Tool Developments Complete and baseline data collected from demonstration site												
Q3 M3: Summer faults artificially injected in demonstration sites and tools successfully implemented within the middleware platform												
Q4 M4: Economic payback estimation of the tools completed and final report finished												
Q1 M2: Demonstration buildings are identified and some baseline data are collected												
Q2 M1: Existing AHU fault diagnosis methods are extended to include active testing and service scheduling recommendation capabilities												
Q2 M3: Fault diagnosis solutions are developed to be VOLTTRON agent(s)												
Q3 M4: Summer testing is finished and data collected												

Please read the complete schedule by double-clicking to open the embedded Excel file (use 100% scale).

BP – Budget Period for Consortium for Building Energy Innovation (formerly EEB Hub)