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

2014 Building Technologies Office Peer Review

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

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Project Summary

Timeline:

Start date: Feb 1st, 2013

Planned end date: April 30th, 2014

Key Milestones

1. Development of cost-effective fault detection and diagnosis strategies for air handling unit (AHU) systems, June 30, 2013
2. Collaborate with UTRC team to generate fault testing data in two demonstration buildings (Building 101 and SWOPE building), April 30, 2014
3. Demonstrate the effectiveness of the developed strategies using existing ASHRAE 1312 and newly generated building data (Building 101 and SWOPE building), April 30, 2014

Budget:

Total DOE $ to date: $369,845

Total cost share to date: $0

Total future DOE $: $322,858 (for 2014-2015)

Total future cost share: $0

Key Partners:

United Technology Research Center
Pacific Northwest National Laboratory

Project Goal:

Develop and demonstrate a library of diagnostics decision support tools that can enable cost effective diagnostics solutions (both embedded and add-on solutions) for existing buildings with a focus on buildings that utilize built-up AHU with variable-air-volume (VAV) and constant-air-volume (CAV) systems

Target Market/Audience:

Buildings: medium sized to large commercial buildings

Audience: control company, service company, fault diagnosis company

Purpose and Objectives

Problem Statement:

- AHU-VAV systems have strong energy and indoor air quality impacts
- Faults are commonly observed in AHU-VAV systems
- Challenges intrinsic to AHU-VAV systems fault diagnosis
  - Lack of sensors and measurement quality
  - “Built-up” (custom) one-of-a-kind systems
  - Multiple operational modes
  - Continuously transient operation
  - Non-linear system
- Market-driven challenges
  - Lack of willingness to invest in automated fault detection and diagnosis (AFDD)
  - Physical system upgrades
  - Engineering time
  - Low tolerance for false alarms
  - Require 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 (18% overall 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 build-in or stand-alone software products for AHU-VAV systems
2. Impact path:
    a. Near-term
        a. Developed strategies are further demonstrated and developed for market adoption
        b. Industrial partners identified
    b. Intermediate-term
        Developed into market ready products and implemented in 5-10 buildings
    a. Long-term
        Products are implemented in more than 50 buildings and are showing substantial energy savings

Approach – AHU Diagnosis

Key challenges addressed

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

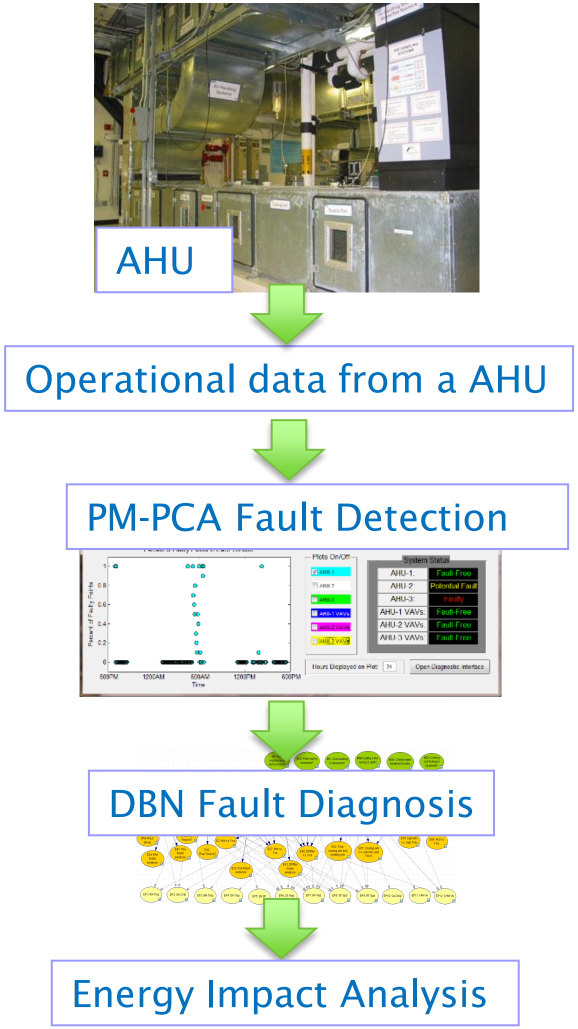
Demonstrated to be effective for all types of faults

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

It is a "Passive" method (no intrusive testing)

Demonstrated using ASHRAE 1312 data and other demonstration building data (Building 101, SWOPE building)

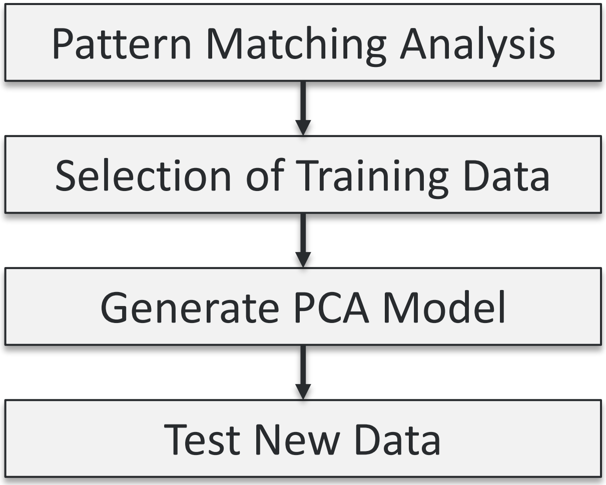
AHU Diagnosis Method overview

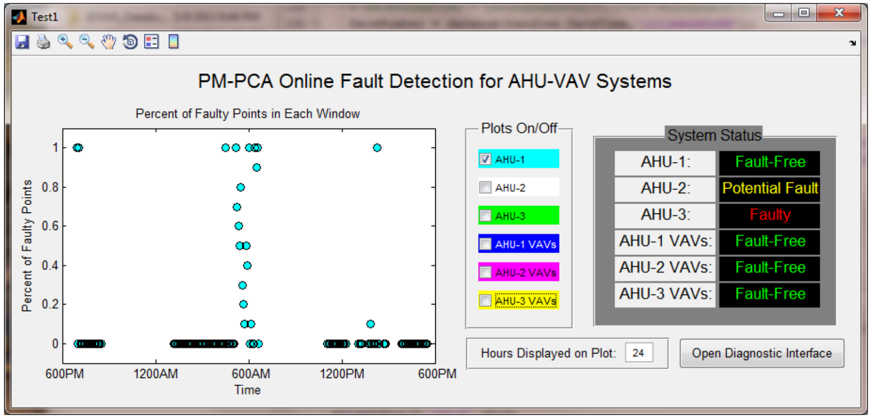


Approach – AHU fault detection method

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)

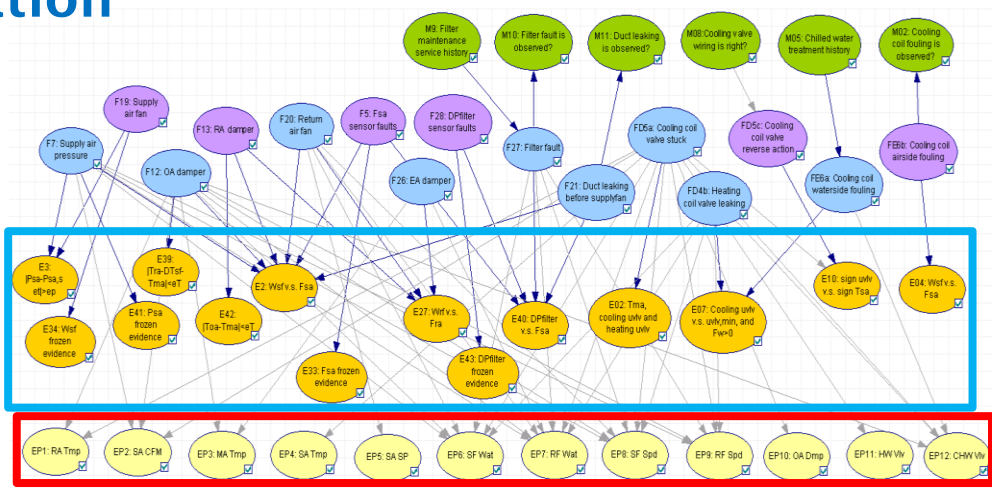




Approach – AHU fault diagnosis method

Bayesian network for fault isolation

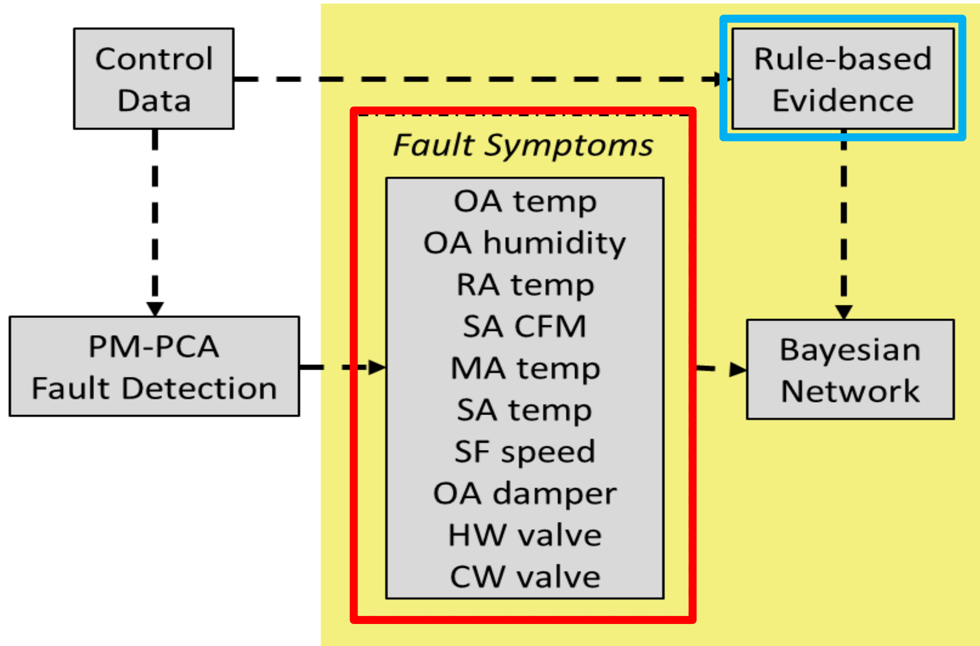
No faulty data training needed!



- 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*"



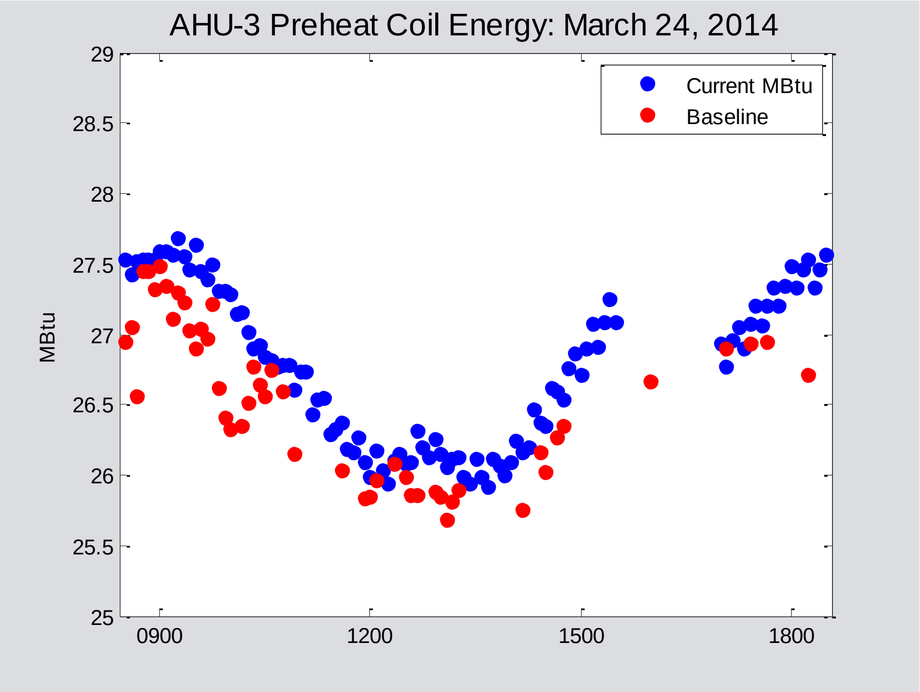
Approach – AHU fault energy impact analysis method

Estimating the energy impact of faults for cost/benefit analyses

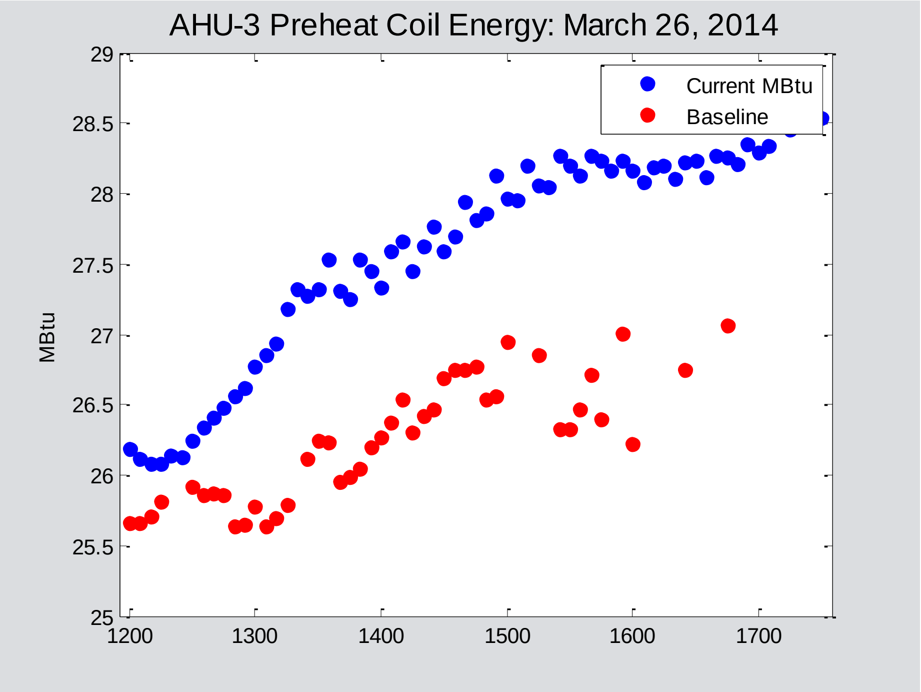
The pattern matching algorithms used for fault detection identifies historical periods of time with similar operating conditions

The same algorithms can also be used to identify “baseline” energy consumption for a given set of operating conditions, and compute the energy impact of faults

Fault-Free



Preheat Valve Stuck at 10% Open



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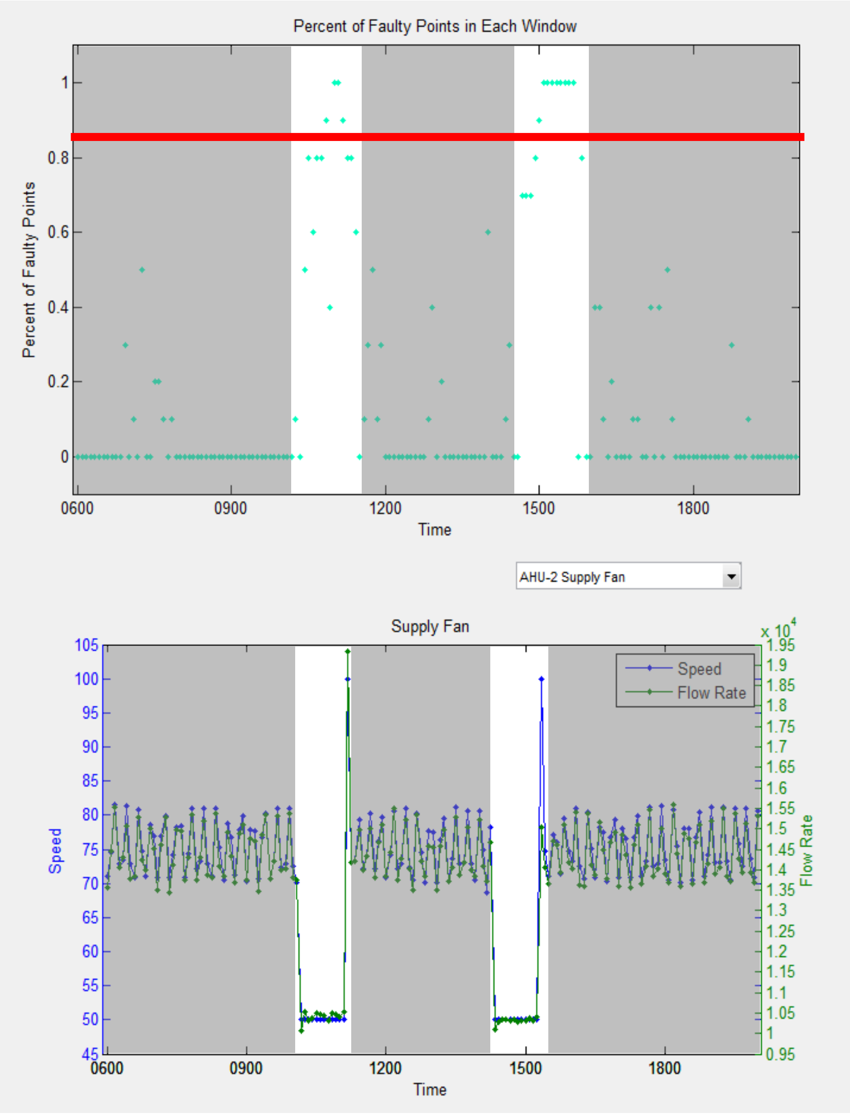
Progress and Accomplishments – fault detection method

PM-PCA Method Results

- Faults are detected when a “window” of time is 90% faulty or more
- Using ASHRAE 1312 data, faults (that had measurable symptoms) consistently detected, and an overall detection rate of 94% was achieved with no false alarms
- All faults with symptoms were also detected at Building 101, with no false alarms

Sample Results from Building 101

Fault Description	Detection Rate	Successful
Supply fan stuck at fixed speed	72%	Yes
Supply air temperature sensor bias	26%	Yes
Leaking preheat valve	41%	Yes
Leaking reheat valve	68%	Yes
VAV damper stuck	43%	Yes
Relative humidity sensor bias	68%	Yes
Outdoor air damper stuck	6%	No



Progress and Accomplishments – fault diagnosis method

Diagnostic Bayesian Network Method Results

ASHRAE 1312 Results

Using the ASHRAE 1312 data, this "combined" Bayesian network was demonstrated to be effective for diagnosing all faults tested:

- Air-side
  - Stuck dampers
  - Duct leakage
  - Coil fouling
  - Fan faults
- Water-side
  - Stuck valves
  - Water-side coil fouling
- Sensor bias/failure faults

Building 101 Implementation

Real-building implementation provided insight into useful method refinements.

- Ability to accept inputs from DX units
  - Cooling stage instead of CW valve
- Formalization/generalization of the threshold training process for plug-and-play implementation.
- Automated weather-station data acquisition for Bayesian network

Initial results are promising, with the diagnostic package automatically identifying both naturally occurring and artificially injected AHU-VAV faults.

Progress and Accomplishments – Energy Impact Method

Method accuracy analyzed by sampling data from fault-free operation

The daily energy usage of each tested AHU (from demonstration buildings) was estimated using the pattern-matching method for 15 randomly selected days, and these values were compared with the measured values at Building 101

Case study: Building 101 AHU-3 Preheat Coil

Under 15 days of normal operation, the method accuracy was studied:

- **Mean error of 0.53% (1.6 MBtu/h), and a median error of 0.66% (1.8 MBtu/h)**
- **Maximum error for any single day was 0.86% (2.8 MBtu/h)**

➔ This means that when the system is fault free, there could still be a difference with baseline data of about **1%** or **3 MBtu/h**

Preheat Coil "stuck" at 10% *(No impact to occupant comfort or zone temperature)*

Compared with fault-free operation	**Heating**	**Free cooling**
Additional energy used (beyond error threshold)	7.4 MBtu/h	336 MBtu/h
Additional natural gas required	7.2 cf/hr	328 cf/hr
Additional Cost	$1.20/day	$54.73/day

Similar studies have been performed under 24 (and counting) unique fault scenarios to help quantify the benefits of automated diagnostics and to assist with informing operators regarding fault prioritization.

All of these studies also include analysis of **AHU fan power**, **cooling equipment power**, and **reheat coil energy**.

Progress and Accomplishments

Lessons Learned:

1) Issues need to be addressed to improve plug/play for fault diagnosis
   - Diagnosis method needs to be developed for AHUs that have other types of control strategies such as demand responsive ventilation
2) Lessons learned during real building demonstration process

Accomplishments: Described in more details in previous slides

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/Recognition: N/A

Project Integration and Collaboration

Project Integration:

- Bi-weekly meetings with partner organizations
- Presentations to stakeholders (IBO workshop, ASHRAE winter conference, IEEE conference etc.)

Partners, Subcontractors, and Collaborators:

UTRC and PNNL

Communications:

"Automated Fault Detection and Diagnosis in AHU-VAV Systems", A. Regnier, J. Wen, and X. Yang, Drexel University, IBO Workshop, June 20-22, 2013, Boulder, CO (Also invited to be presented in ASHRAE winter conference)

Regnier, A., Yang, X.B., and Wen, J., "Pattern Matching PCA for Fault Detection in Air Handling Units", IEEE CASE, Madison, WI, August 2013

Next Steps and Future Plans

Next Steps and Future Plans:

- Extend the self-learning PM-PCA and DBN fault diagnosis methods to be a VOLTTRON agent
- Include active diagnosis method developed by PNNL
- Further reduce training data need and improve plug/play features
- Provide service scheduling recommendations based on fault energy impact, occupant comfort impact, and service cost
- Demonstrate the developed strategies in three SMSCB buildings
- Identify potential industrial partner(s) to develop the strategies to products

Project Budget

Project Budget: 2013-2014: $229,126; 2012-2013: $140,719; 2014-2015: $322,858

Variances: None

Cost to Date: : 2013-2014: $229,126; 2012-2013: $140,719;

Additional Funding: None

Budget History					
02/01/2012 – FY2013 (past)		FY2014 (current)		FY2015 – 04/30/2015(planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$140,719	$0	$229,126	$0	$322,858	$0

Project Plan and Schedule

Project Schedule		
Project Start: 02/01/2013		Completed Work
Projected End: 4/30/2014		Active Task (in progress work)
		Milestone/Deliverable (Originally Planned) use for missed milestones
		Milestone/Deliverable (Actual) use when met on time

	FY2013				FY2014				FY2015			
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)
Past Work												
Q1 Milestone: Fault Injection Plan Complete												
Q2 Milestone: FDD Tool Developments Complete												
Q2 Milestone: Baseline Data Collected from Demos												
Q3 Milestone: Summer faults artificially injected												
Q3 Milestone: Tools implemented in middleware												
Q4 Milestone: Economic estimation completed												
Q4 Milestone: Final Report Complete												
Current/Future Work												
Q3 Milestone: Extended to include active testing												
Q4 Milestone: Developed to be VOLTTRON agent												
Q4 Milestone: Demonstration tests finished												