EXECUTIVE SUMMARY

Demonstration of a Building Automation System Embedded Performance Degradation Detector Using Virtual Water/Air Flow Meters

ESTCP Project EW-201407

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1.0 INTRODUCTION

The *Department of Defense Budget Priorities and Choices – FY 2014*, calls for more effective heating, ventilation and air conditioning (HVAC) metering, which requires precise measurement of HVAC airflow and water flow rates. A building automation system (BAS) embedded performance degradation detector (PDD), with the additional measurements provided by low-cost virtual air/water flow meters, is one of the technologies that has the potential to reduce DoD energy costs by approximately $0.3 Billion per year (relative to the DoD goal of $1.5 Billion annual savings) based on the results in a laboratory environment test.

Existing industrial standards, e.g., American Society of Heating, Refrigeration, Air-conditioning Engineers (ASHRAE) Standards 62.1 and 90.1, set up detailed *advanced energy efficient operations*. However, some approaches cannot readily be implemented in HVAC systems because of *the lack of low cost, reliable water and airflow meters.* HVAC system airflow and water flow rates are key controlled variables, which impact indoor environmental quality, equipment safety, and system energy performance. For example, a lower supply airflow rate may cause poor indoor ventilation, while a higher supply airflow rate may cause excessive use of fan power and reheat energy. For a variable chilled water loop, a lower water flow rate may damage chillers while a higher water flow rate may cause an excessive use of pump power. Airflow and water flow rates are also essential indices to evaluate energy performance of HVAC systems. Flow rates can be used to simultaneously measure *actual* energy use and project the *reference* (fault-free) energy usage based on energy balance and/or mechanism of subsystems. For example, the actual energy usage of cooling coils can be measured by water flow rates. At the same time, the reference value (fault-free) of energy usage can be also projected by airflow rates based on energy balance. Deviations between actual and reference energy usage and air/water flow rates are always indicators of faults and inefficient operations. *Consequently, the lack of flow measurements leads to inadequate energy performance evaluation indices for HVAC system operations.* Efforts to commission buildings and improve energy performance are similarly limited without BAS-embedded metering capacities. Today, energy efficiency measurements require professionals to travel to each facility with portable meters. Embedded metering within BAS will save labor-related costs while providing more accurate and timely data.

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2.0 OBJECTIVES

The goal of the proposed PDD demonstration project was to improve the energy efficiency of DoD buildings while maintaining or improving indoor air quality by increasing building energy management intelligence, using low cost and reliable virtual flow meter technologies. Specifically, the technical objectives were to:

1. Validate energy savings, costs and benefits of the proposed technologies, including the virtual flow meters and the PDD.

2. Document findings and guidelines from the demonstration to promote low-cost virtual meter implementation through existing DoD energy meter policies and encourage widespread adoption of the BAS-embedded PDD in DoD buildings.

3. Enable technology transfer through the demonstration by showcasing benefits of the technology to increase DoD and vendor acceptance, making the technology available across DoD agencies and facilities.

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3.0 TECHNOLOGY DESCRIPTION

The demonstrated technology includes two major elements: virtual meter technology and PDD algorithms.

3.1 VIRTUAL METER TECHNOLOGY

The virtual flow meter technology is a key component of the PDD in the proposed project. Three different types of virtual meters significantly enhance the measurement capacity of the BAS. In Type 1 meters, the whole building level chilled water flow rate and hot water flow rate are virtually obtained using pump operational characteristics, namely a **pump flow meter.** In Type 2 meters, the airflow rate in each air handling unit (AHU) is virtually obtained using fan operational characteristics, namely a **fan flow meter.** The chilled water flow rate in each AHU is virtually obtained in Type 3 meters using control valve operational characteristics, namely a **control valve flow meter**. The water flow rate through the cooling coil, airflow rate, and chilled/hot water flow rate through each main duct or pipe are regulated by the valve movement and the fan and pump speed adjustment. As a result, the virtual meters installed in this project used both available or inexpensive/easy methods to obtain measurements of operational variables, such as valve position, differential pressure across the valve, fan/pump head and motor input power and frequency, and device characteristic curves that relate the behavior of these devices to the desired virtual values and commonly measurable variables. Device characteristic curves can be determined empirically using measurements or analytically from first principles. The desired virtual values can then be calculated using measured values of variables for which meters are commonly installed.

3.2 PUMP/FAN FLOW METER

Both the virtual pump and fan flow meters work under the same principle. Motor input power (W) is determined by useful mechanical work imparted into fluid, the product of head (H) and flow rate (Q), fan/pump efficiency and motor efficiency. Theoretically, the fan/pump efficiency ($\eta_{f/p}$) is a function of the ratio of head (H) to flow rate (Q) squared, while motor efficiency (η_{motor}) is theoretically a function of power (W), frequency (f), and voltage (V). Practically, head can be measured by a pressure differential sensor while voltage, power and frequency can be obtained through the existing variable frequency drive (VFD). Meanwhile, the fan/pump efficiency curve can be calibrated through experiments on each system. Using calibrated motor and fan/pump efficiencies (η_{motor} and $\eta_{f/p}$), the flow rate (Q) can be obtained numerically based on the fan/pump head (H) and VFD output power (W), as well as the VFD output frequency (f) and voltage (V), shown in Equation (E-1) below.

$$Q = \frac{W \cdot \eta_{motor}(W,f,V) \cdot \eta_{f/p}(\frac{H}{Q^2})}{H} \qquad \text{(E-1)}$$

3.3 VIRTUAL VALVE FLOW METER

A cooling or heating energy meter is typically not installed in an AHU because of high installation and maintenance costs and increased water loop pressure drop. It is often impossible to install one in existing AHUs due to space and system dimension limitations. The virtual valve flow meter uses existing coil control valve operational variables to indirectly obtain the water flow rates.

Theoretically, the pressure drop through a valve is determined by valve position and flow rate for a given valve, which has a fixed valve characteristic curve. The pressure drop can be measured by a water pressure differential sensor, and the valve position can be obtained by either valve command through a BAS or valve position feedback from the valve actuator. The valve characteristic curve needs to be obtained through a calibration process. Therefore, the flow rate (Q) can be obtained based on the pressure drop ($\Delta P_{L,x}$) and valve position (x) as well as calibrated valve curve ($F_{L.x}$), as described in Equation (E-2).

$$Q = F_{L.x}(x)\sqrt{\Delta P_{L,x}} \qquad \text{(E-2)}$$

3.4 PERFORMANCE DEGRADATION DETECTION (PDD)

The PDD uses the available BAS data plus the measurements from the proposed virtual flow meters at pumps, fans, and valves to determine actual energy usage of key building systems and subsystems. The energy usage and air/water flow rates of energy efficient operations for those systems (i.e., reference values for practices conforming to standards and guidelines set by ASHRAE and other authorities), can also be obtained through virtual flow measurements based on energy balance and/or mechanisms of subsystems. As a result, the actual energy usage and reference energy uses for fans, reheats, and cooling coils in AHUs and pumps, as well as chillers and boilers in chilled and hot water systems, can be automatically obtained in Phase I, Data Collection. Besides the energy comparison, the duct and water loop pressure setpoints for fan and pump speed can be calculated based on the virtual flow measurements. *The variation between the measured and simulated setpoints indicates a faulty setpoint or the incorrect damper or valve position.* By comparing the actual energy use/setpoint with the reference energy uses/setpoint, the energy degradation or system malfunction operations can be determined in Phase II, Online Diagnosis. The severity of the performance degradation or faults will trigger alarms and motivate facility operators for quick corrections and is shown by the empty box to the right of the detector module. The mechanism of the detector is shown in Figure E-1. The shaded box bordered by the dashed line represents an add-in PDD (a set of function modules) in a BAS. The two boxes on the left represent available sensor and command information in a BAS.

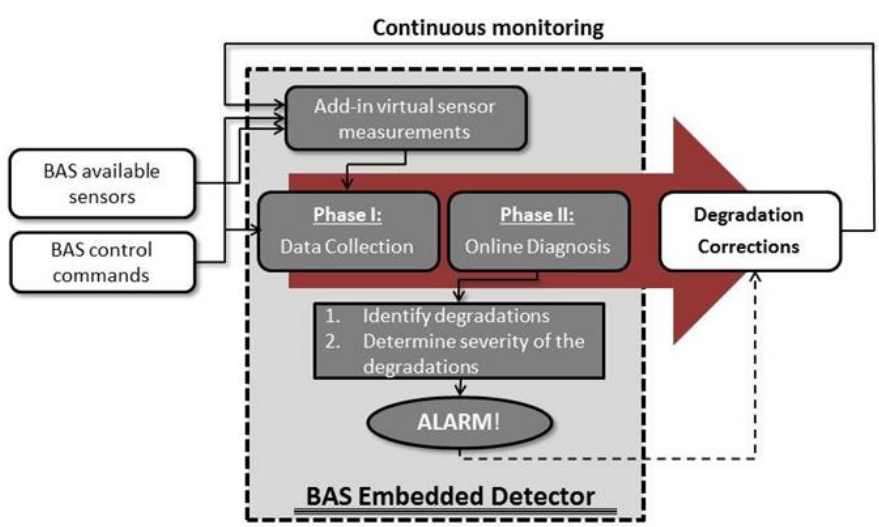

Figure E-1. Flow Chart of the Embedded PDD.

4.0 PERFORMANCE ASSESSMENT

The newly constructed clinic building at the Tinker Air Force Base (TAFB) in Oklahoma City, OK, was chosen as the demonstration site. The building, with a floor area of 162,000ft^2, has standard building operating hours from 8:00am to 5:00pm. The building consists of two (300 tons each) chillers along with three primary chilled water pumps at 7.5 HP each, three secondary chilled water pumps at 20HP each, and three condensing water pumps at 20 HP each. The heating system is served by two (3,348MBH each) boilers with three primary hot water pumps at 3HP each and two secondary pumps at 25HP each. The central plant is located on the ground floor. Both chilled water and hot water loops are formed as primary and secondary water loop systems. A total of 13 AHUs serve in the entire building. Of these, 11 AHUs have both supply air return air fans and two AHUs have supply air fans only.

The project team installed virtual flow meters for the technology demonstration on all supply and return air fans, the cooling coil control valves, all secondary pumps including hot water and chilled water pumps, primary chilled water pumps, and condensing water pumps. The hardware installations included 24 air differential pressure transducers, 24 water differential pressure transducers, and 6 variable frequency drives on the 3 primary chilled water pumps and 3 condensing water pumps. However, because the building was operational, the facility was not ready to shift the current constant flow primary loop and condensing loop to variable flow systems due to constant unreliable chiller operations. The project team did not make any operational changes to the pumps on the primary and condensing loops. Additionally, the project team programmed the corresponding virtual flow rate calculation algorithms and PDD algorithms in the BAS.

4.1 PERFORMANCE ASSESSMENT FOR VIRTUAL METER TECHNOLOGY

The virtual flow meter demonstration encompassed two phases. The first phase was to use the original proposed flow rate calculation algorithms to calculate the flow rate, and the second phase used the improved algorithms built on the lessons learned through this demonstration project. The results of the first phase virtual flow meter demonstration were submitted for mid-progress report review in November 2015 (in Appendices E, F and G). At that time, the project team had documented that 85% of the virtual fan flow meters, 30% of the valve flow meters and 75% of the virtual pump flow meters passed the success criterion, which is less than 2% error at 95% confidence. Over 90% of the virtual meters passed 3% error at 95% confidence. The project team had since concluded that the sacrificed error is due to the following reasons:

1. The motor harmonic loss increases as the VFD frequency decreases. The motor efficiency variations under different frequencies were not reflected in flow rate calculation algorithms that the project team originally proposed.
2. Dynamic control valve behavior has a significant impact on valve flow rate calculation, especially when a valve experienced slow position change. The steady-state model adopted in the original virtual valve flow meter calculations did not consider this impact.
3. A loose belt was another factor that caused virtual fan flow sensor errors.
4. The project team selected a 25PSI measurement range of differential pressure (DP) transducers for virtual valve flow meters according to the design information. However,

the project team observed that the dynamic feature of the operational system can easily exceed this threshold. There were several periods during which the DP transducers reached maximum capacity because the range of the DP was not large enough.

5. The return fan is interactive with the supply fan. As a result, the return fan operated with a negative fan head when the return fan speed was low and the supply fan speed was high. The virtual fan airflow calculation algorithms do not apply to this abnormal fan operation.

The mid-progress report was approved by the ESTCP office in March 2016. Since that time, the project team has continued efforts to improve the accuracy of the virtual flow meters, especially for the errors caused by the first two reasons listed above, by revising the flow calculation algorithms to consider motor efficiency loss due to the harmonics by low VFD frequencies and the valve dynamic behavior. The project team has also added a new PDD algorithm to detect the loose fan belt problem for the facility to resolve the third reason listed above. Items 4 and 5 above required hardware replacements to address these issues, which were prohibited by budget constraints.

Due to time constraints, the project team could not implement the new algorithm in all units. The improved virtual flow meter models were implemented in the secondary chilled water and hot water pumps and the supply air fans in AHU2 and AHU13. The results of the four test units showed that the accuracy of the virtual flow meter was improved by 15% to 20% compared with the calculated flow rate using the originally proposed algorithm. The accuracy improvement also depends on how frequently the evaluated points fall under low motor frequency operations. Meanwhile, to describe the valve dynamic behavior, a BAS-programmable algorithm was developed to convert the valve commands to the true valve position by factoring in the impacts of resolution errors, valve stiction, and deadband. The correction algorithm was implemented in the virtual valve flow meters in AHU2 and AHU13 for test purposes. The results showed that valve flow meter accuracy was improved by 40% to 45% compared with the valve flow rate calculated using the original algorithm without the corrections. As a result, with the improvements made in the flow rate calculation algorithms, the virtual flow rate errors were reduced significantly compared with the results in the mid-term report. If a 15% to 20% improvement was applied to the errors of the fan/pump flow meters summarized in the mid-progress report, the uncertainty of all the fan/pump flow meters would be less than 1.2% at 95% confidence. If the 40% to 45% improvement was applied to the errors of all valve low meters summarized in the mid-progress report, the uncertainty of 10 out of 13 valve flow meters would be less than 1.1% error at 95% confidence; three would be between 2% and 3% error at 95% confidence.

4.2 PERFORMANCE ASSESSMENT FOR PDD TECHNOLOGY

The goal of the PDD was to identify energy saving opportunities in the demonstration building through the PDD. The performance assessment approach was to commission the building first to make sure the building was in a fault-free condition (i.e., used as the equipment performance baseline in the PDD algorithms), then manually generate faults to validate the effectiveness of the PDD responses, and correct the problems that the PDD identified to validate the savings that otherwise would be lost if the PDD was not in place. The operation parameters and/or energy usage before and after corrections at the system level and for the whole building were both collected to validate the system performance improvement and the energy savings. The implemented PDD included detection of excessive outdoor air intake using the cooling energy calculated by the virtual valve flow rate in each AHU, simultaneous heating and cooling detection using the virtual

fan flow meter, fan operation-related faults and pump operation-related faults using the virtual fan/pump flow meter, and accessory signals such as fan/pump head and fan/pump motor power. Through the demonstration, the installed PDD was found to be effective in detecting the proposed faults. When the cooling energy in an AHU was used as an energy index to detect the excessive outdoor air intake faults, an outdoor air humidity sensor was necessary to increase the sensitivity of this fault detection method. Due to the lack of an outdoor air humidity sensor, the installed PDD for outdoor air detection can only detect the outdoor air faults that result in more than 15% cooling energy loss.

To validate the whole building level energy performance and savings, the project team collected monthly utility bills from January 2014 through December 2017, a total of four years of data. The improvements by the project team were primarily made from January 2016 to May 2016. The facility operators overrode all the AHUs to 24-hour operations in mid-July 2016 with 5°F lower supply air temperature to correct an observed mold risk. The overrides significantly altered the energy performance of the building. Therefore, the project team selected the energy usage data in Year 2015 as a baseline and the energy usage data in Year 2017 for after the improvements. Although the supply air temperature overrides were released in late 2016, the schedule overrides were still not completely released, i.e., there were still several AHUs running 24x7 at the present time. The savings were compromised by this operational change.

The energy savings was the difference between the baseline energy (2015) and the energy after the PDD implementation (2017). However, weather impacts need to be considered. A scatter chart is used to regress the energy usage versus average outdoor air temperature before and after the corrections to eliminate weather impacts. Figure E-2 shows the monthly electricity usage versus average outdoor air temperature in each month, while Figure E-3 shows the monthly natural gas usage before and after the correction versus the monthly average outdoor air temperature. The red triangles denote the months before the correction and the green dots denote the months after the correction. By using the linear regression of the red triangles and green dots respectively, shown by the solid lines in both figures, the average electricity and natural gas usage versus average outdoor air temperature values are obtained. The difference between the two solid lines in Figure E-2 was the electricity savings, equivalent to 14.7% of the electricity usage baseline. The difference between the two solid lines in Figure E-3 was the natural gas savings, equivalent to 16.9% of the natural gas usage baseline. For Year 2017 weather conditions, the average annual total cost savings was $74,629 for the whole building level energy usage based on the lumped utility rate of $0.0522/kWh for electricity and $4.02/MMbtu (the utility rates were calculated using the average rates from 2014 to 2017 due to the rate changes over time), equivalent to 15% annual energy cost savings overall.

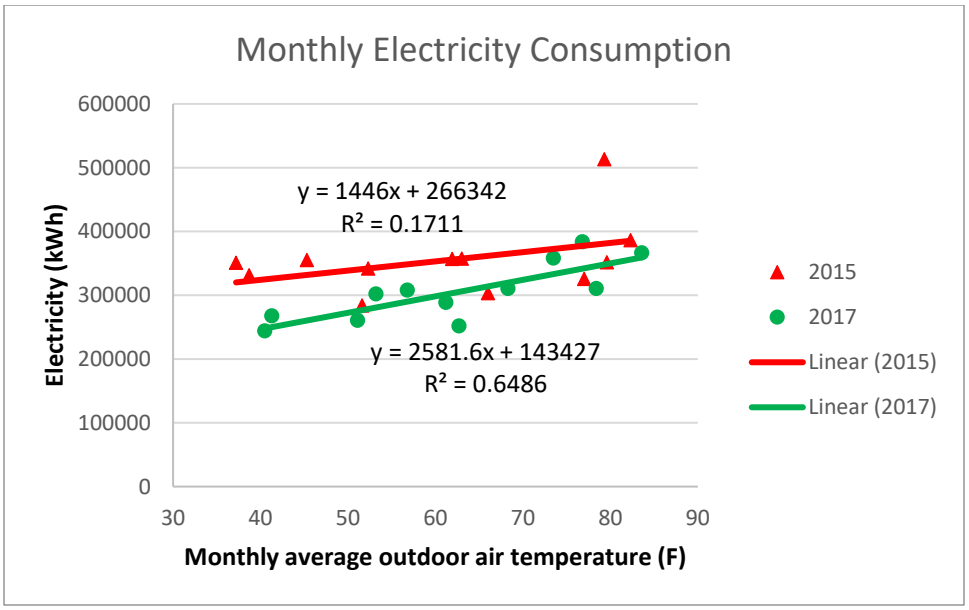

Figure E-2. Monthly Electricity Use vs. Monthly Average Outdoor Air Temperature.

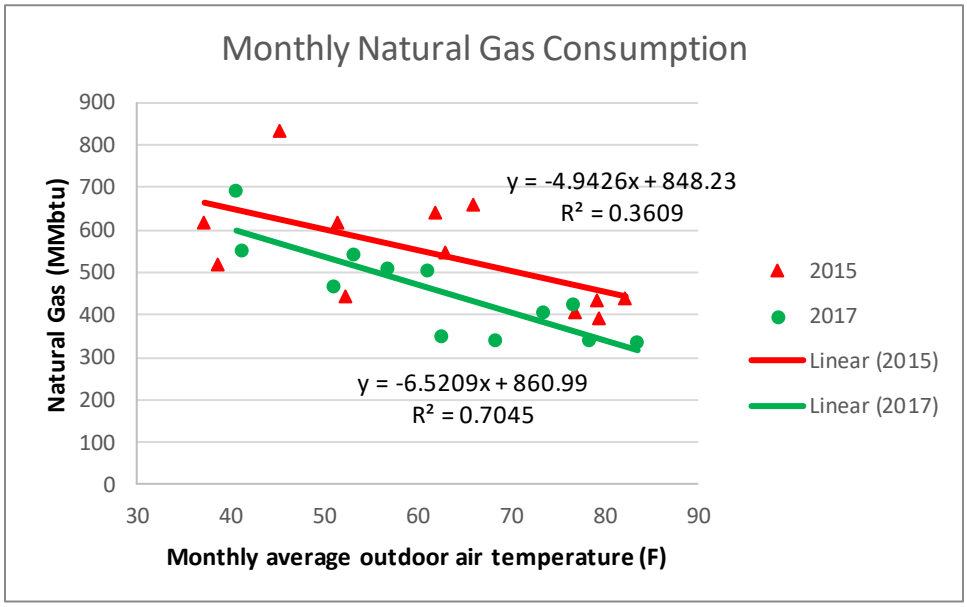

Figure E-3. Monthly Natural Gas Usage vs. Monthly Average Outdoor Air Temperature.

5.0 COST ASSESSMENT

The cost of the installations of virtual meters and the PDD is shown in Table E-1. The hardware costs were estimated using the actual subcontractor's invoice in the demonstration project and the programming costs were estimated based on actual engineering effort needed to implement the algorithms in the BAS. For the demonstration building, the total construction cost of PDD was $97,170 and total cost including soft corrections of the faults and deficiencies identified through PDD was $110,295. The measured savings of the building was $74,629. Therefore, the simple payback was 1.5 years.

Table E-1. Cost Assessment.

Cost Element	Data Tracked During the Demonstration	Estimated Costs
Hardware capital costs	Subcontractor's invoice	$62,705 (the costs of six VFDs was deducted because they did not contribute to the savings we obtained)
Installation costs	Subcontractor's invoice	$19,465 (the costs of six VFDs was deducted because they did not contribute to the savings we obtained)
Programming and PDD implementation costs	Estimates based on the engineering programming effort by the project team	$15,000 (estimated by assuming 200 engineering hours were needed at a rate of $75 per hour)
Facility operational costs	Reduction in energy required vs. baseline data	$74,629 (The savings was obtained by correcting the faults/deficiencies identified through PDD.)
Maintenance	• Frequency of required maintenance • Labor and material per maintenance action	$0 (Not beyond routine maintenance costs. Particularly for this project, no equipment replacement was needed for the 15% savings we obtained. However, our team made soft corrections on fan and pump operation set points, outdoor air intake and VAV box minimum airflow setting, estimated at $13,125 one-time engineering cost for the correction at $75 per hour for a total of 175 hours.)
Hardware lifetime	Estimate based on components degradation during demonstration	50 years
Annual service costs	Based on 50 engineering hours annually	$3,750 ($4^{+}$ hours per month)

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6.0 IMPLEMENTATION ISSUES

The project was successfully demonstrated with measurable savings and an attractive payback. More importantly, our project team learned a lot through the process that not only helped us to enhance the technology, but also prepare us for a better understanding of future technology commercialization. We have summarized three possible implementation issues below that can help us facilitate a realistic commercialization plan to promote the virtual flow meters and PDD technology across the DoD installations.

- Potential regulation issues: the major regulation issue is cybersecurity clearance. Although we did not have this trouble during this project because the BAS we needed to access is a standalone system (i.e., it is not on the Tinker network system), project cost can potentially increase due to the extra time and effort required to obtain necessary cybersecurity clearance.
- End-user concerns: It is not realistic to train facility operators to use the PDD technology, including reading the alarms and making necessary corrections for energy savings. This approach would potentially increase the workload of the staff and potentially could increase the need for additional staffing. Instead, we have learned through the demonstration that a more economical and practical approach would be to hire contractors who can be either BAS service providers or our technology licensees (the PDD technology installers) by paying a small monthly fee to receive the alarms and make necessary soft changes in programs if needed and/or suggest hardware replacements to the facility operators.
- Procurement issues: There are two approaches to implement the technology. One is the same as we did in the demonstration project, i.e., implement the calculation algorithms into the existing BAS, and the other is to install our mini-converter, which includes flow rate calculations and then outputs the signal directly to the BAS. The first approach has no procurement issues, as all accessories to be installed are off-the-shelf. The second approach may need special procurement procedures because our mini-converter is currently a custom-built prototype.