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TO: Jin Wen, Chair TC 7.5, jinwen@drexel.edu
Li Song, Research Subcommittee Chair TC 7.5, lsong@ou.edu
William Murphy, Research Liaison Section 7.0, William.murphy@uky.edu

FROM: Michael Vaughn, MORTS, MORTS@ASHRAE.net

DATE: January 23, 2019

SUBJECT: Work Statement (1875-WS), "Develop cost and performance indices to evaluate effectiveness of virtual airflow meters in HVAC application"

During their recent winter meeting, the Research Administration Committee (RAC) reviewed the subject Work Statement (WS) and voted to return with comments.

Below are the issues, concerns, and questions that must be addressed in your next submission of the WS if you choose to resubmit.

1. Estimated time and cost both are too high.
2. The labor index is the most uncertain part of the proposed project, and could cause prospective bidders to steer away from it.
3. Clearly define objectives.

Please coordinate changes to this Work Statement with your Research Liaison, William Murphy, William.murphy@uky.edu or RL7@ashrae.org prior to resubmitting it to the Manager of Research and Technical Services for further consideration by RAC.

Also, it is necessary that you provide a new TC vote on the revised Work Statement, and a letter describing how each of the above items were addressed in the revision.

If you wish for this work statement to be reconsidered at the next RAC meeting, the revised Work Statement must be sent (electronically) to Michael Vaughn, Manager of Research and Technical Services (morts@ashrae.net) by **March 15, 2019**. The next opportunity for consideration after this deadline is May 15, 2019.

Check List Criteria	Voted NO	Comments & Suggestions
Project ID	**1875**	
Project Title	**Develop cost and performance indices to evaluate effectiveness of virtual airflow meters in HVAC application**	
Sponsoring TC	TC 7.5, (Smart Building Systems)	
Cost / Duration	$250,000 / 24 Months	
Submission History	**1st WS Submission, RTAR Accepted F15**	
Classification: Research or Technology Transfer	Basic/Applied Research	
RAC 2019 Winter Meeting Review	**RTAR STAGE FOLLOWED**	
State-of-the-Art (Background): The WS should include some level of literature review that documents the importance/magnitude of a problem. If not, then the WS should be returned for revision. **RTAR Review Criterion**		
Advancement to the State-of-the-Art Is there enough justification for the need of the proposed research. Will this research significantly contribute to the advancement of the State-of-the-Art. **RTAR Review Criterion**		
Relevance and Benefits to ASHRAE: Evaluate whether relevance and benefits are clearly explained in terms of: a. Leading to innovations in the field of HVAC & Refrigeration b. Valuable addition to the missing information which will lead to new design guidelines and valuable modifications to handbooks and standards. Is this research topic appropriate for ASHRAE funding? If not, Reject. **RTAR Review Criterion**		
IF THE THREE CRITERIA ABOVE ARE NOT ALL SATISFIED - MARK "REJECT" BELOW BUT ADDRESS THE FOLLOWING CRITERIA AS APPROPRIATE		
Detailed Bidders List Provided? The contact information in the bidder list should be complete so that each potential bidder can be contacted without difficulty.		**10** - 5 listed including emails.
Proposed Project Description Correct? Are there technical errors and/or technical omissions that the WS has that prevents it from correctly describing the project? If there are, than the WS needs major revision.		**10**- Need to add uncertainty analysis. **5** - concerns about the maturity of the virtual air flow sensors. **13** - Your Objectives 3 and 4 are generic and apply to virtual sensors of all types, whereas Task 3 and 4 specifically refer to virtual airflow sensors. Objectives 3 and 4 should probably be targeted toward airflow sensors.
Task Breakdown Reasonable? Is the project divided into tasks that make technical and practical sense? Are the results of each task such that the results of the former naturally flow into the latter? If not, then major revisions are needed to the WS that would include: adding tasks, removing tasks, and re-structuring tasks among others.		**12** - #5 in the objectives should be rewritten to reflect "validation of the virtual sensors" **10** - 6 Tasks defined with deliverables for each task. **5** - scope is too broad **13** - Task 1 seems to be too broad. While the project is focused on airflow, this task asks the PI to look at all virtual sensors, which could be VERY extensive. The labor cost estimation of Tasks 3 and 4 seems challenging to me. If many virtual airflow sensors are incorporated using energy management systems, the time it takes to develop a virtual airflow sensor will depend on how familiar the programmer is with the system and perhaps how easy the EM system is to program. The time/effort it takes a programmer to develop their first one may be an order of magnitude greater than for their second one. While hardware is more easily quantifiable, this programming effort seems to not be so easy to quantify. **4**- The task descriptions are clear and have good detail
Adequate Intermediate Deliverables? The project should include the review of intermediate results by the PMS at logical milestone points during the project. Before project work continues, the PMS must approve the intermediate results.		**12** - well structured intermediate deliverables that are correlated with the task breakdown. **7** - I would suggest and additional milestone be added for evaluation at the end of either Task 2 or Task 3, to include a decision stage gate to confirm that viable applications are available that warrant field/lab testing efforts.
Proposed Project Doable? Can the project as described in the WS be accomplished? If difficulties exist in the project's WS that prevent a successful conclusion of the project, then the project is not doable. In this situation, major revision of the WS is needed to resolve the issues that cause the difficulty.		**8** - There is no guarantee that a suitable technical approach will be revealed but the effort to determine this limitation is still a positive outcome. **5**- scope is too broad. **13** - The labor index seems to be too undefined for a bidder to know what is to be measured and and how to quantify it.
Time and Cost Estimate Reasonable? The time duration and total cost of the project should be reasonable so that the project can be as it is described in the WS.		**10** - Cost is too high but duration is OK. **13** - 24 months seems somewhat long for the six tasks, and the $250k seems quite high even for a 24 month project. **4** - I would like better understanding of the cost and duration of this project. $250K seems high?, maybe not Can we obtain co-funding for ASHRAE as well?
Proposed Project Biddable? Examining the WS as a whole, is the project described in the WS of sufficient clarity and detail such a potential bidder can actually understand and develop a proposal for the project? This criterion combines the previous three criteria into an overall question concerning the usefulness of the WS. If the WS is considered to not be biddable, then either major revisions are in order or the WS should be rejected.		**10** - After reducing cost. **7** - Subject to consideration of incorporating a decision stage gate prior to embarking on field/lab testing. **5** - I have concerns that this project will take much longer than estimated and the project is not biddable. **13** - The labor index is the most uncertain part of the proposed project and could cause prospective bidders to steer away from it. If additional details or parameters could be given about what the labor cost would entail, it may make it easier for a bidder to understand what they must do in Tasks 3 and 4.

Decision Options	Initial Decision	Final Approval Conditions
ACCEPT		**12** - I think that overall it is a well written WS except for minimal typos and grammatical mistakes. **10** - PES and PMS members not identified. Fix typos. **7** - The work statement made it much clearer the objective of the research, the need that the research will address, and the benefit that will result if a successful application can be developed. With this well established, it it still not certain that there will be a workable, reliable solution for virtual sensing of air flow will be revealed. For this reason, I feel it is important to include a decision stage gate before field/lab testing is performed. **5** - I am concerned that this research would be a low value investment. **13** - I would suggest you be somewhat more focused on virtual airflow meters in the literature search and provide better guidance on what constitutes labor effort for Tasks 3 and 4. Estimated time and cost may both be high. **4** - I would like better understanding of the cost and duration of this project. $250K seems high?, maybe not Can we obtain co-funding for ASHRAE as well?
COND. ACCEPT		
REJECT		

ACCEPT Vote - Work statement(WS) ready to bid as-is
CONDITIONAL ACCEPT Vote - Minor Revision Required - RL can approve WS for bid without going back to RAC once TC satisfies RAC's approval condition(s) to his/her satisfaction
RETURN Vote - WS requires major revision before it can bid
REJECT Vote - Topic is no longer considered acceptable for the ASHRAE Research Program due to duplication of work by another project or because the work statement has a fatal flaw(s) that makes it unbiddable

WORK STATEMENT COVER SHEET

Date: November 23, 2018

(Please Check to Insure the Following Information is in the Work Statement)

A. Title	X
B Executive Summary	X
C. Applicability to ASHRAE Research Strategic Plan	X
D. Application of the Results	X
E. State-of-the-Art (background)	X
F. Advancement to State-of-the-Art	X
G. Justification and Value to ASHRAE	X
H. Objective	X
I. Scope	X
J. Deliverables/Where Results will be Published	X
K. Level of Effort	
Project Duration in Months	X
Professional-Months: Principal Investigator	X
Professional-Months: Total	X
Estimated $ Value	X
L Proposal Evaluation Criteria & Weighting Factors	X
M. References	X
N. Other Information to Bidders (Optional)	

Title:

Develop cost and performance indices to evaluate effectiveness of virtual airflow sensors in HVAC applications

WS# **1875**

(To be assigned by MORTS - Same as RTAR #)

Results of this Project will affect the following Handbook Chapters, Special Publications, etc.:

ASHRAE handbook HVAC applications
Ch40: Computer application
Ch42: Supervisory control strategies and optimization
Ch61: Smart building systems

Responsible TC/TG: TC7.5

Date of Vote: 12/3/18

For		8
Against	*	0
Abstaining	*	1(Chair)
Absent or not returning Ballot	*	0
Total Voting Members		9

This W/S has been coordinated with TC/TG/SSPC (give vote and date):
n/a

Has RTAR been submitted? Yes
Strategic Plan
Theme/Goals

Work Statement Authors: **
Li Song

Proposal Evaluation Subcommittee:
Chair:
Members:

Project Monitoring Subcommittee:
(If different from Proposal Evaluation Subcommittee)

Recommended Bidders (name, address, e-mail, tel. number): **

Haorong Li, University of Nebraska – Lincoln, hli3@unl.edu, 405-554-3271
Gang Wang, University of Miami, g.wang2@miami.edu, 305-284-5555
Tom Lawrence, University of Georgia, lawrence@engr.uga.edu
Gene Havard, Bosch TT (FHP manufacturing), Gene.Havard@us.bosch.com
Mingsheng Liu, Bes-tech Inc., mliu@bes-tech.net

Potential Co-funders (organization, contact person information):

(Three qualified bidders must be recommended, not including WS authors.)

	Yes	No	How Long (weeks)
Is an extended bidding period needed?		v	
Has an electronic copy been furnished to the MORTS?	v		
Will this project result in a special publication?		v	
Has the Research Liaison reviewed work statement?		v	

* Reasons for negative vote(s) and abstentions

** Denotes WS author is affiliated with this recommended bidder
Use additional sheet if needed.

WORK STATEMENT# 1875

Title:

Develop cost and performance indices to evaluate effectiveness of virtual airflow meters in HVAC application

Sponsoring TC/TG/MTG/SSPC:

TC 7.5 - Smart Building Systems

Co-Sponsoring TC/TG/MTG/SSPCs (List only TC/TG/MTG/SSPCs that have voted formal support)

n/a

Executive Summary:

Existing standards, e.g., ASHRAE standards 62.1 (2016a) and 90.1(2016b), set up detailed *advanced energy efficient operations*. However, some approaches cannot be implemented in HVAC systems because of *the lack of low cost, reliable airflow sensors.* Virtual meters provide an alternative low-cost solution. “Virtual meters” in the context of this document are referred to the measurements that are **obtained through calculations using the available measurements data for other variables along with mathematical models**. The calculations are usually programmed in a Building Automation System or a standalone device. **Therefore, the virtual measurements are not from a device assembled and calibrated by a manufacturer and therefore do not have a calibration certification to users**. The uncertainty of virtual flow rate measurements is propagated from the accuracy of the mathematical model and the error of measured inputs through the mathematical models. Although capital costs are generally small, the cost of virtual meters is associated with labor costs for model identification and calibration. Unlike physical sensors, which are characterized by the direct (capital) costs and accuracies given by the manufacturers, there are no standard criteria to characterize and evaluate virtual meters. As virtual meters are becoming more important in HVAC controls and diagnosis, standardizing criteria for these purposes for virtual sensors becomes extremely important so the value and cost of their use can be compared to traditional hardware sensors. Due to large number of virtual meters introduced in literatures, for a reasonable work scope, this project is designed for the study of virtual airflow meters because physical airflow rate measurements are critical and yet expensive, sometime not even feasible in HVAC systems due to the space limitation.

Applicability to the ASHRAE Research Strategic Plan:

The results of this project are directly in support of Goal 1 in the Research Strategic Plan:
Goal 1: Maximize the actual operational energy performance of buildings and facilities.
More specifically, the results of this project will enable a proper and fair evaluation approach of virtual airflow meters, which will allow industry to adopt the virtual meter technology with confidence. Once adopted, the virtual meter technology will provide significant amount of additional HVAC system operation measurements at extremely low costs. The additional data measured by the virtual airflow meters will provide high resolution monitoring capacity to a building to reduce faults and improve energy efficiency in a timely manner, so buildings can perform more efficiently.

Application of Results:

The outputs of this project will assist the development of a standardized virtual meter cost and performance metrics.

State-of-the-Art (Background):

The concept of virtual sensors has been widely adopted by the automobile industry over the last two decades, e.g., the techniques used to estimate tire pressure by sensing and comparing the rate of each tire rotation (Gustafsson et al., 2001) (Carlson and Gerdes, 2005) (Dementjev, 2007). Virtual meter concepts are not new to the HVAC industry. In 2004, Lee and Dexter [2005] published the development of a fuzzy sensor for measuring the average temperature of the air leaving the mixing-box of an air-handling unit (AHU) because the accuracy of conventional mixed air temperature measurement was limited by space constraints. In their study, a fuzzy relationship between the temperature measured by a conventional sensor and the actual average mixed air temperature was determined through computational dynamic simulations of the mixing chamber, with the results used to correct the errors of the mixed air temperature measured with the conventional physical sensor. Wichman and Braun (2008) further improved the applicability of the virtual mixed air temperature sensor by integrating the temperature calculation with the AHU operational conditions such as outdoor air damper positions. For reliable chiller plant control, an indirect building cooling load measurement was introduced by Huang et al. (2008). In their development, the electricity consumption of the chiller compressors was combined with chiller efficiency models to predict the actual cooling output from the chillers. In addition, Li and Braun [2009] developed a set of virtual sensors for enhancing rooftop AHU operation. For example, the development of a virtual refrigerant charge sensor (Li and Braun, 2009), a virtual refrigerant pressure sensor (Li and Braun, 2009), and a virtual supply air temperature sensor (Yu et al., 2011) has provided a set of low-cost viable methods to better facilitate rooftop AHU optimal operation, fault detection, and diagnosis. In addition, by using pressure drop measurements, valve position, and a calibrated valve curve, a virtual valve flow meter was developed (Swamy et al. 2012; Song et al. 2013). Wang et al. (2018) and Andiroglu et al. (2016) compared the accuracy of the virtual pump meters with the accuracy of conventional flow meters finding that the coefficient of determination or R-squared for the entire validation period is 0.97. Currently, the valve flow meter and pump flow meter are both used for built-up HVAC system fault detection and diagnosis. Rivas Prieto (2017) identified an effective in-site fan curve calibration procedure for virtual airflow meter application.

In summary, virtual sensors currently under development for use in HVAC systems calculate, i.e. indirectly measure, the values for variables that are either too expensive or impossible to measure. The uncertainty of virtual flow rate is propagated from the accuracy of the model and the error of measured inputs through the mathematical models. Although capital costs are generally small, the cost of virtual meters is associated with labor costs for model identification and calibration. Unlike physical sensors, which are characterized by the direct (capital) costs and accuracies given by the manufacturers, there are no standard criteria to characterize and evaluate virtual meters.

Advancement to the State-of-the-Art:

Airflow rate is a key controlled variable of HVAC systems, which impacts 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. In addition to high meter and installation costs (for example, a duct mounted airflow measurement station costs $4.5K), physical meter installations require long, straight and unobstructed ducts, equivalent to 7.5 diameters upstream and 3 diameters downstream of physical flow meters for proper measurements (ASHRAE Handbook, 2017). Space limitations plus expensive installation costs are the most dominant factors discouraging physical flow meter installations in existing buildings. Virtual airflow meters are a promising alternative. However, **the virtual measurements are not from a device assembled and calibrated by a manufacturer and therefore do not provide enough confidence to users.** “Virtual meters” in this context are referred to the measurements that are obtained through on-site assembling, in either Building Automation System or a standalone device, the available measurements data for other variables using mathematical models. The uncertainty of virtual flow rate is propagated from the accuracy of model and the error of measured inputs through the mathematical models. Although capital costs are generally small, the cost of virtual meters is associated with labor costs for model identification and calibration. Unlike physical sensors, which are characterized by the direct (capital) costs and accuracies given by the manufacturers, there are no standard criteria to characterize and evaluate virtual meters. As virtual meters are becoming more important in HVAC controls and diagnosis, standardizing criteria for these purposes for virtual sensors becomes extremely important so the value and cost of their use can be compared to traditional hardware sensors. This project is the first study in regard and it is expected the outcome of the project will provide necessary knowledge to establish a standard or a guide to assess the performance of virtual meters.

Justification and Value to ASHRAE:

On average about 30% of building energy use is wasted as a result of inefficient and faulty system operations. Due to lack of metering capacity in HVAC systems, such energy waste cannot be identified in a timely manner. Virtual sensors provide a low-cost solution for high-resolution metering capacity, which will allow the energy waste to be identified promptly. Creating performance indices for virtual sensors aligns well with No.1 Goal that is described in ASHRAE Strategic Plans, "Maximize the actual operational energy performance of buildings and facilities". As virtual sensors become increasingly available for use in HVAC system control and operations, standard criteria to evaluate the effectiveness of virtual sensors will become an urgent need; this project will satisfy this need. The successful completion of the project will provide virtual-sensor cost and performance evaluation indices, which are not available today. The outcome of the project will enable sound comparison of virtual and physical sensors for HVAC applications and promote use of virtual sensing technology where it is the most practical and cost-effective sensing option. The broader use of the virtual sensors will enhance building monitoring and control and capture energy savings by eliminating waste. Eventually this will contribute towards achieving energy efficiency and sustainability.

Objectives:

The objectives to be met by this project are:

1. Conduct a literature survey on virtual sensor uses in general, including in other industries, to identify how virtual meters are evaluated in other industries.
2. Conduct a comprehensive study of publications on virtual airflow sensors in HVAC applications and categorize them based on the amount of independent input variables, parameters and governing equations.
3. Develop appropriate indices to characterize and evaluate virtual sensors for HVAC applications.
4. Develop experimental test procedures for evaluating the indices developed in Task 3 for PMS approval.
5. Select three representative virtual airflow sensors and test them against high precision physical sensors.
6. Document the resulting performance indices for virtual sensor cost and performance evaluations.

Scope/Technical Approach:

The project aims at developing matrices for the cost and performance evaluation of virtual airflow meters. Following six tasks are designed to obtain the project objectives.

Task 1: Literature review

In this task, a comprehensive literature review will be performed in the following areas: 1) Virtual meter use in general, including in other industries; 2) Cost and performance evaluation approach/matrices in other industries if available; 3) Virtual meters in HVAC industry with focus on virtual airflow meters.

The deliverable of this task is a report that summarizes the literature review.

Task 2: Categorization of available virtual airflow meter in HVAC industry.

In this task, the available virtual airflow meters in literatures will be categorized based on their working mechanism, such as the amount of independent input variables, parameters and models (governing equations) for the flow rate calculations. Three representative virtual flow meters will be selected for further study.

The deliverable of this task is a report that summarizes the different types of the virtual airflow meters and the three representative meters as candidates for the study.

Task 3: Identify key indices to evaluate the cost and performance of the three representative virtual airflow meters.

In order to evaluate performances of the virtual airflow meters, indices such as physical requirements, complex of the models, measurement performance, cost of hardware and labor for meter calibration, and system adoptions etc., need to be identified and defined in this task. The indexes shall be divided into three categories: a) performance including accuracy and time response, such as time constant; b) indexes that associated with hardware costs (determined by needed inputs and parameters for the models); and c) indexes that associated with labor costs in calibration. The calibration costs are usually related to the model adopted in the virtual flow calculation. Therefore, the effort for the calibration needs to be quantified through the number of parameters needed in the model and error propagation analysis of how the errors in the parameters and the accuracy of the model can contribute to the errors in the virtual measurements.

The deliverable of this task is a report defining and summarizing the indexes to be used in the proposed evaluation methodology.

Task 4: Develop experimental test procedures to evaluate the indices developed in Task 3.

The experimental test is to test the performance and cost of the selected three representative virtual airflow meters. In this section, the project team is required to make a thorough experiment design plan, so the objectives of the experiments can be served. A total three types of tests are required, as described below:

1. Accuracy tests: The accuracy of the three representative virtual flow meters need to be compared with high precision flow meters for both high and low airflow rate conditions. Errors need to be given in absolute and relative manners for both low and high flow rate conditions. The test can be done in a lab or field environments, but there is a requirement for the flow rate variations for the tests.
2. Time response tests: Time response is another important characteristic for meters since the most

meters are applied for control purpose. Therefore, the time response of the three virtual meters need to be tested with abrupt load changes including fan speed changes and other control signal changes to evaluate the time responses of the virtual airflow meters under both high and low airflow conditions through the comparison with physical flow meters.

3. Repetition tests: The project team needs to propose and justify the number of the repetitions for the test purpose.
4. Cost quantification: Costs include the hardware costs and labor cost for the model calibration. The actual labor effort needs to be documented and recorded to precisely determine the labor costs. Factors that impact the labor cost are expected to be summarized as well in order to generalize the cost calculation for a broader application.

In order to successfully execute the three types of tests, the project team is required to design a detailed plan for 1) Test apparatus design and 2) Test procedure design.

The deliverable of this task is a report summarizing the test design and procedures.

Task 5: Test the three representative virtual flow meters against the high precision physical flow meters.
Upon an approval of the PMS committee on the experimental design, the project team will carry on the equipment installation, testing and the experiment result analysis in this task.

The deliverable of this task is a report summarizing the test setup and test results.

Task 6: Identify and document the resulting performance indices for virtual meter cost and performance evaluations.
Based on the findings from Task 1 to 5, the project team will identify the key indices of the virtual airflow meter evaluation matrix. In addition, a standard testing method to obtain the indices of the matrix is also required for the future industry adoption. The project team is also required to analyze the limitation of adopting the indices and method to other types of the virtual meters if there is any. Suggestions of the future work needs to be summarized to address the limitation.

The deliverable of this task is a report documenting the indices, the method and their limitation for other types of the virtual meters.

Deliverables/Where Results Will Be Published:

The deliverables are defined with each task and described above. Bidders must include an itemized checklist confirming that they have included each task/sub-task deliverable in their response.

In addition, progress, Financial, Interim, and Final Reports, Research or Technical Paper(s), and Data shall constitute required deliverables ("Deliverables") under this Agreement and shall be provided as follows:

a. Progress and Financial Reports

Progress and Financial Reports, in a form approved by the Society, shall be made to the Society through its Manager of Research and Technical Services at quarterly intervals; specifically, on or before each January 1, April 1, June 10, and October 1 of the contract period.

Furthermore, the Institution's Principal Investigator, subject to the Society's approval, shall, during the period of performance and after the Final Report has been submitted, report in person to the sponsoring committee at the annual and winter meetings, and be available to answer such questions regarding the research as may arise.

b. Final Report

A written report ("Final Report") in a form approved by the Society, shall be prepared by the Institution and submitted to the Society's Manager of Research and Technical Services by the end of the Agreement term, containing complete details of all research carried out under this Agreement. An electronic copy of the Final Report in Microsoft Word or PDF format shall be furnished for review by the PMS.

Following approval by the PMS and the sponsoring committee, in their sole discretion, final copies of the Final Report will be furnished by the Institution as follows:

- An executive summary in a form suitable for wide distribution to the industry and to the public.
- Two copies on CD-ROM; one in PDF format and one in Microsoft Word.
- Science & Technology for the Built Environment or ASHRAE Transactions Technical Papers

One or more papers shall be submitted first to the ASHRAE Manager of Research and Technical Services (MORTS) and then to the "ASHRAE Manuscript Central" website-based manuscript review system in a form and containing such information as designated by the Society suitable for publication. Papers specified as deliverables should be submitted as either Research Papers for Science & Technology for the Built Environment or Technical Paper(s) for ASHRAE Transactions. Research papers contain generalized results of long-term archival value, whereas technical papers are appropriate for applied research of shorter-term value, ASHRAE Conference papers are not acceptable as deliverables from ASHRAE research projects. The paper(s) shall conform to the instructions posted in "Manuscript Central" for an ASHRAE Transactions Technical or Science & Technology for the Built Environment paper. The paper title shall contain the research project number (1783-RP) at the end of the title in parentheses, e.g., (1783-RP).

Note: A research or technical paper describing the research project must be submitted after the TC has approved the Final Report. Research or technical papers may also be prepared before the project's completion, if it is desired to disseminate interim results of the project. Contractor shall submit any interim papers to MORTS and the PMS for review and approval before the papers are submitted to ASHRAE Manuscript Central for review.

c. Data

The Institution agrees to maintain true and complete books and records, including but not limited to

Deliverables/Where Results Will Be Published (Continued):

notebooks, reports, charts, graphs, analyses, computer programs, visual representations etc., (collectively, the “Data”), generated in connection with the Services. Society representatives shall have access to all such Data for examination and review at reasonable times. The Data shall be held in strict confidence by the Institution and shall not be released to third parties without prior authorization from the Society, except as provided by GENERAL CONDITION VII, PUBLICATION. The original Data shall be kept on file by the Institution for a period of two years after receipt of the final payment and upon request the Institution will make a copy available to the Society upon the Society's request.

d. Project Synopsis

A written synopsis totaling approximately 100 words in length and written for a broad technical audience shall be submitted to the Manager of Research and Technical Services by the end of the Agreement term for publication in ASHRAE Insights. The synopsis should document the main findings of research project, why findings are significant, and how the findings benefit ASHRAE membership and/or society in general.

The Society may request the Institution submit a technical article suitable for publication in the Society's ASHRAE JOURNAL. This is considered a voluntary submission and not a Deliverable. All Deliverables under this Agreement and voluntary technical articles shall be prepared using dual units; e.g., rational inch-pound with equivalent SI units shown parenthetically. SI usage shall be in accordance with IEEE/ASTM Standard SI-10.

Level of Effort:

It is estimated that the project will require two (2) professional-month for the Principal Investigator and twenty-four (24) months effort of a research assistant, with a project duration of twenty-four (24) months at a cost of $250,000.

Proposal Evaluation Criteria:

No.	Proposal Review Criterion	Weighting Factor
1	Contractor's understanding of Work Statement, FDD tools, and FDD MOT as revealed in proposal	15%
2	Quality of methodology proposed for conducting research.	20%
3	Contractor's capability in terms of facilities, and access to existing AHU FDD tools (including commercial products) and existing AHU fault data.	30%
4	Qualifications of personnel for this project.	20%
5	Student involvement.	5%
6	Probability of meeting the objectives and schedule of the Work Statement (including past ASHRAE projects, if applicable).	10%

Project Milestones:

No.	Major Project Completion Milestone	Deadline Month
1	**The test plan for three representative virtual airflow meters is completed**	**12**
2	**Three types of tests are completed.**	**18**
3	**Final report is completed.**	**24**

Authors:

Li Song, TC 7.5;

References:

ANSI/ASHRAE Standard 62.1-2016, Ventilation for acceptable indoor air quality

ANSI/ASHRAE/IES Standard 90.1-2016, Energy standard for buildings except for low-rise residential buildings

ASHRAE, 2017 ASHRAE Handbook – Fundamentals

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Huang, G., Wang, S., Sun, Y. 2008. Enhancing the reliability of chiller control using fused measurement of building cooling load, *HVAC&R RESEARCH*, Volume 14 (6): pages 941-958.

Lee, P.S., Dexter, A. I. 2005. A fuzzy sensor for measuring the mixed air temperature in air-handling units, *Measurement*, Volume 37(1): page 83–93.

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Rivas Prieto, A., Thomas, W. M., Song, L., Wang, G. 2017. In-situ fan curve calibration for virtual airflow sensor implementation in VAV systems, *ASHRAE Transactions*, Vol. 123 (1): 215-229.

Wichman, A., Braun. J.E. 2009, A smart mixed-air temperature sensor, *HVAC&R RESEARCH*, Volume 15 (1): pages 101-115.

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Other Information for Bidders (Optional):

Feedback to RAC and Suggested Improvements to Work Statement Process

Now that you have completed the work statement process, RAC is interested in getting your feedback and suggestions here on how we can improve the process.

Shaping Tomorrow's Built Environment Today

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TO:	Natascha Miles Ferretti, Chair TC 7.5, natascha.milesi-ferretti@nist.gov Jin Wen, Research Subcommittee Chair TC 7.5, jinwen@drexel.edu
CC:	Philip Haves, Research Liaison, 7.0, phaves@lbl.gov
FROM:	Michael Vaughn, MORTS, mvaughn@ashrae.org
DATE:	November 20, 2015
SUBJECT:	Research Topic Acceptance Request (1783-RTAR), "Develop cost and performance indices to evaluate effectiveness of virtual sensors in HVAC applications"

During their annual meeting, the Research Administration Committee (RAC) reviewed the subject Research Topic Acceptance Request (RTAR) and voted to accept with comments it for further development into a work statement (WS) provided that the key comment(s) and question(s) below are addressed to the satisfaction of your Research Liaison, Philip Haves, phaves@lbl.gov, or RL7@ashrae.net, in the work statement draft.

1. The overall project objectives are vague and too general right now. Suggest for the WS that the TC define some specific applications where development of virtual sensors would provide clear benefit in terms of energy efficiency or fault detection. If a finite number of applications were identified, a more realistic research project could be defined around these specific applications. As currently described, this work is too broad to be successful or fully understood.

2. WS should also better define the approach that will be used. What control/measurement/diagnostic tasks should be undertaken by the virtual sensors? What parameters will be measured? Which parameters are needed to improve the control or diagnostics of "HVAC Systems" or a smaller more specific set of equipment for this project?

3. Consideration should be given by the TC to conducting at least a limited literature survey prior to writing the work statement in order to better scope this project.

The work statement draft must be approved by the Research Liaison prior to submitting it to RAC.

An RTAR evaluation sheet is attached as additional information and it provides a breakdown of comments and questions from individual RAC members based on specific review criteria. This should give you an idea of how your RTAR is being interpreted and understood by others. Some of these comments may indicate areas of the RTAR and subsequent WS where readers require additional information or rewording for clarification.

The first draft of the work statement should be submitted to RAC no later than **August 15, 2017** or it will be dropped from display on the Society's Research Implementation Plan. The next likely submission deadline for a new work statement on this topic is **May 15, 2016** for consideration at RAC's 2016 Annual meeting. The submission deadline after that for work statements is **August 15, 2016** for consideration at the RAC's 2016 fall meeting.

Project ID	**1783**	
Project Title	**Develop Cost and Performance Indices to Evaluate Effectiveness of Virtual Sensors in HVAC Applications**	
Sponsoring TC	TC 7.5 (Smart Building Systems)	
Cost / Duration		
Submission History	**1st Submission**	
Classification: Research or Technology Transfer	Technology Transfer	
RAC 2015 Fall Meeting Review		
Essential Criteria	**Voted NO**	**Comments & Suggestions**
Background: The RTAR should describe current state of the art with some level of literature review that documents the importance/magnitude of a problem. References should be provided. If not, then note it in your comments.		
Research Need: Based on the background provided is the need for additional research clearly identified? If not, then the RTAR should be rejected.	**13**	**13** - The RTAR does not establish that there is a problem or need that virtual sensors will address. **10** - Need to develop methods that could form the basis of a standard MOT is well described.
Relevance and Benefits to ASHRAE: Evaluate whether relevance and benefits are clearly explained in terms of: a. Leading to innovations in the field of HVAC & Refrigeration b. Valuable addition to the missing information which will lead to new design guidelines and valuable modifications to handbooks and standards. Is this research topic appropriate for ASHRAE funding? If not, Reject.	**13, 10**	**13** - Virtual sensors in the simplest form have been used in control systems for years. They are simply referred to as calculated points. For example, once temperature and relative humidity are sensed, many other psychrometric parameters (such as dew point) can be calculated and used by automated building control systems. It is not clear that sophisticated cost and performance indices are needed. **2** - 24 months may be too short period to complete the work considering the need for two literature surveys, developing indices and finally validation. **11** - This project relates to more complex 'calculated points' where there is some uncertainty in the model used in the calculation. **10** - I found this proposal really interesting, but at the end I have two major problems with it. (1) The crux seems to be that there are no standard criteria to measure the **effectiveness** of virtual sensors (Research Need), but that term is not really defined. Instead we have a couple of potentially important criteria, such as sensitivity, presented. (2) I'm familiar with too many products that already incorporate these, particularly in the sense of 'smart' motor controllers that use things like RPM and torque to compute air flow, and comparable advances in AC product diagnostics from smart compressor feedback. I'm not sure i see an important or catalytic ASHRAE role, but my vision may be too limited.
IF ABOVE THREE CRITERION ARE NOT <u>ALL</u> SATISFIED - MARK "REJECT" BELOW & CONTINUE REVIEW BELOW		
Other Criteria	**Voted NO**	**Comments & Suggestions**
Project Objectives: Based on the background and need, evaluate whether the project objectives are: 1. Aligned with the need 2. Specific 3. Clear without ambiguity 4. Achievable If not, then appropriate feedback should be provided.	**9, 6**	**9** - Projects Objectives are a bit ambiguous. **2** - It is unclear which parameters will be controlled by the virtual sensors. **6** - It is not clear what and how many types of "virtual sensors" will be studied, and their application scenarios. The RTAR uses "HVAC systems" which is too broad. **11** - Main application is to diagnostics, less to control. Principles and performance metrics are quite generic.
Expected Approach and Budget: Is there an adequate description of the approach in order for RAC to be able to evaluate the appropriateness of the budget? If not, then the RTAR should be returned for revision. Anticipated funding level and duration:	**15, 9**	**15** - Prefer to see a description of the approach here rather than merely checking the boxes. **9** - Expected Approach can be modified in order to be practically understandable. **2** - No approach available. The project is quite interesting, but not very specific. What control/measuring tasks should be undertaken by the virtual sensors. What parameters will be measured? Which parameters are needed to improve control of HVAC system
References: Are the references provided?		
Decision Options	**Initial Decision?**	**Final Approval Conditions**
ACCEPT AS-IS		**7** - Experimental approach is not described. The objectives are vague and too general. There are a lot of variability in the real world. It is not clear how a virtual sensor can be generalized unless it is a very narrow specific and non variable application. **13** - Suggest the TC define some specific applications where development of virtual sensors would provide clear benefit in terms of energy efficiency or fault detection. If a finite number of applications were identified, a more realistic research project could be defined around these specific applications. As currently described, this work is too broad to be successful. **9** - Project objectives should be limited. Maybe Indoor Climate Control, or Refrigerating machine control, or Thermal storage trunk control, or something. If the target is limited, research result become more concrete and such the results will be easily applied for other equipment. **2** - 1/3 of the committee did not vote. RTAR should be more specific on what is going to happen. Also two literature surveys make me quite nervous, shouldn't they be done prior to writing the RTAR?
ACCEPT W/COMMENTS		
REJECT		

ACCEPT Vote - Topic is ready for development into a work statement (WS).
ACCEPT W/COMMENTS Vote - Minor Revision Required - RL can approve RTAR for development into WS without going back to RAC once TC satisfies RAC's approval condition(s)
REJECT Vote - Topic is not acceptable for the ASHRAE Research Program

Research Topic Acceptance Request Cover Sheet

Date: 6/28/2015

(Please Check to Insure the Following Information is in the Work Statement)

- A. Title ✔
- B. Applicability to ASHRAE Research Strategic Plan ✔
- C. Application of the Results ✔
- D. State-of-the-Art (background) ✔
- E. Advancement to State-of-the-Art ✔
- F. Justification and Value to ASHRAE ✔
- G. Objective ✔
- H. Estimated Duration ✔
- I. References ✔

Title:
Develop cost and performance indices to evaluate effectiveness of virtual sensors in HVAC applications

RTAR# 1783
(To be assigned by MORTS)

Results of this Project will affect the following Handbook Chapters, Special Publications, etc.:

ASHRAE handbook HVAC applications
Ch40:Computer application/Ch42:Supervisory control strategies and optimization/Ch61:Smart building systems

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Responsible TC/TG: TC7.5

Date of Vote: 6/30/15

For		8
Against	*	0
Abstaining	*	0
Absent or not returning Ballot	*	4
Total Voting Members		12

Co-sponsoring TC/TG/MTG/SSPCs (give vote and date):

RTAR Lead Author: Li Song

Expected Work Statement Lead Author: Li Song

Potential Co-funders (organization, contact person information):

Research Classification:

- [x] Basic/Applied Research
- [ ] Advanced Concepts
- [ ] Technology Transfer

	Yes	No
Has an electronic copy been furnished to the MORTS?	✔	
Has the Research Liaison reviewed the RTAR?	✔	

* Reasons for negative vote(s) and abstentions

Not returning ballot.

DRAFT RTAR Template

Title: Develop cost and performance indices to evaluate effectiveness of virtual sensors in HVAC applications

Summary

Describe in summary form the proposed research topic, including what is proposed, why this research is important, how it will be conducted, and why ASHRAE should fund it (50 words maximum)

This project is to provide standard cost and performance indices to evaluate the effectiveness of virtual sensors. Virtual sensors currently under development for use in HVAC systems combine available sensor measurements with mathematical models to indirectly estimate the values for variables that are either too expensive or impossible to measure. The uncertainty of virtual sensors is propagated from measured inputs through the models. The cost of virtual sensors is associated with labor costs for model identification and calibration. Capital costs are generally small. Unlike physical sensors, which are characterized by the direct (capital) costs and accuracies given by the manufacturers, no standard criteria exist to characterize and evaluate virtual sensors. As virtual sensors are becoming more important in HVAC controls and diagnosis, standardizing criteria for these purposes for virtual sensors becomes extremely important so the value and cost of their use can be compared to traditional hardware sensors.

Background

Provide the state of the art with key references (at the end of this document) substantiating it (300 words maximum)

The concept of a virtual sensor has been widely adopted by the automobile industry over the last two decades, e.g., the techniques used to estimate tire pressure by sensing the rate of tire rotation [Gustafsson et al., 2001] [Carlson and Gerdes, 2005] [Dementjev, 2007]. Virtual meter concepts are not new to the HVAC industry. In 2004, Lee and Dexter [2004] published the development of a fuzzy sensor for measuring the average temperature of the air leaving the mixing-box of an air-handling unit (AHU) because the accuracy of conventional mixed air temperature measurement was limited by space constraints. In their study, a fuzzy relationship between the temperature measured by a conventional sensor and the actual average mixed air temperature was determined through computational dynamic simulations of the mixing chamber, with the results used to correct the errors of the mixed air temperature measured with the conventional physical sensor. Wichman and Braun [2008] further improved the applicability of the virtual mixed air temperature sensor by integrating the temperature calculation with the AHU operational conditions such as outdoor air damper positions. For reliable chiller plant control, an indirect building cooling load measurement was introduced by Huang et al. [2008]. In their development, the electricity consumption of the chiller compressors was combined with chiller efficiency models to predict the actual cooling output from the chillers. In addition, Li and Braun [2009] developed a set of virtual sensors for enhancing rooftop AHU operation. For example, the development of a virtual refrigerant charge sensor [Li and Braun, 2009], a virtual refrigerant pressure sensor [Li and Braun, 2009], and a virtual supply air temperature sensor [Li et al., 2011] has provided a set of low-cost viable methods to better facilitate rooftop AHU optimal operation, fault detection, and diagnosis. In addition, by using pressure drop measurements, valve position, and a calibrated valve curve, a virtual flow meter was developed (Swamy et al. 2012; Song et al. 2011, 2012). Wang et al. (2013a) and Andiroglu et al. (2013) compared the accuracy of the pump virtual meters with the accuracy of conventional flow meters finding that the coefficient of determination or R-squared for the entire validation period is 0.97. Currently, the valve flow meter and pump flow meter are both used for built-up HVAC system fault detection and diagnosis.

Research Need

Use the state of the art described above as a basis to specify the need for the proposed effort (250 words maximum)

As virtual sensors have become effective alternatives to physical sensors for enhancing HVAC system controls and operation, it becomes increasingly important to have standard criteria to characterize and evaluate the effectiveness of virtual sensors. Unlike physical sensors, which are evaluated by direct sensor and installation costs and accuracies given by manufacturers, there are no standard criteria available to evaluate the effectiveness of virtual sensors. Virtual sensors currently under development for use in HVAC systems combine available sensor measurements (e.g., temperatures and pressures) with mathematical models to indirectly estimate the values for variables that are either too expensive or impossible to measure in HVAC systems. The uncertainties in virtual sensor measurements are propagated from measured inputs through the models. Therefore, it is important to evaluate the need for performance indicators such as min/max values and the sensitivity of the virtual sensor to its inputs. Plans include developing a systematic framework for evaluating the performance of virtual sensors.

Furthermore, the costs of virtual sensors are associated primarily with labor costs for model identification and calibration rather than capital cost as with conventional hardware sensors. Decisions regarding when to use a physical sensor and when to use a virtual sensor require comparable indices. Therefore, standard procedures are needed to 1) quantify the uncertainties in virtual sensor measurements by taking into account modeling uncertainty and 2) determine the true costs of virtual sensors by including labor costs for installation, model identification, and calibration. The results will enable sound comparison of virtual and physical sensors for HVAC applications and promote virtual sensing technology to become widely available

Project Objectives

Based on the identified research need(s), specify the objectives of the solicited effort that will address all or part of these needs (150 words maximum)

The objectives to be met by this project are:

1. Conduct a literature survey on virtual sensor uses in other industries to identify how virtual meters are evaluated in other industries.
2. Conduct a comprehensive study of publications on virtual sensors in HVAC applications and categorize them based on the amount of independent input variables, parameters and governing equations.
3. Develop appropriate indices to characterize and evaluate virtual sensors for HVAC applications.
4. Develop experimental test procedures for evaluating the indices developed in Task 3 for PMS approval.
5. Select three representative virtual sensors and test them against high precision physical sensors.
6. Document the resulting performance indices for virtual sensor cost and performance evaluations.

Expected Approach

Describe in a manner that may be used for assessment of project viability, cost, and duration, the approach that is expected to achieve the proposed objectives (200 words maximum).

Check all that apply: Lab testing ☐, Computations ☐, Surveys ☑, Field tests ☑, Analyses and modeling ☑, Validation efforts ☐, Other (specify) ( )

Relevance and Benefits to ASHRAE

Describe why this effort is of specific interest to ASHRAE, its impact, and how it will benefit ASHRAE and the society. How does it align with ASHRAE Strategic Plans and Initiatives? How does it advance the state of the art in this area in general? Are there other stakeholders that should be approached to obtain relevant information or co-funding? (350 words maximum)

On average about 30% of building energy use is wasted as a result of inefficient and faulty system operations. Due to lack of metering capacity in HVAC systems, such energy waste cannot be identified in a timely manner. Virtual sensors provide a low cost solution for high-resolution metering capacity, which will allow the energy waste to be identified promptly. Creating performance indices for virtual sensors aligns well with No.1 Goal that is described in ASHRAE Strategic Plans, "Maximize the actual operational energy performance of buildings and facilities". As virtual sensors become increasingly available for use in HVAC system control and operations, standard criteria to evaluate the effectiveness of virtual sensors will become an urgent need; this project will satisfy this need. The successful completion of the project will provide virtual-sensor cost and performance evaluation indices, which are not available today. The outcome of the project will enable sound comparison of virtual and physical sensors for HVAC applications and promote use of virtual sensing technology where it is the most practical and cost effective sensing option. The broader use of the virtual sensors will enhance building monitoring and control and capture energy savings by eliminating waste. Eventually this will contribute towards achieving energy efficiency and sustainability.

Anticipated Funding Level and Duration

Funding Amount Range: $ 200k

Duration in Months: 24 months

References

List the key references cited in this RTAR

Andiroglu, E., Wang, G., Song, L.2013. Development of a virtual water flow meter using pump head and motor power. Zero Energy Mass Customization Housing (ZEMCH2013) International Conference, Miami, FL.

Carlson, C. R., Gerdes, J. C. 2005. Consistent nonlinear estimation of longitudinal tire stiffness and effective radius, IEEE Transactions on Control Systems Technology, Volume 13(6): page1010–1020.

Dementjev, A., Ribbecke, H. D., Kubin, H., Kabitzsch, K. 2007. Strategy of virtual measurement for optimization of dynamic dead-time processes in automated control systems. Proceedings of 5th International Conference on Industrial Informatics INDIN, Volume 1: page 565-569.

Gustafsson, F. Drev¨o, M., Forssell, U., L¨ofgren, M., Persson, N., Quicklund, H. Virtual sensors of tire pressure and road friction, Society of Automotive Engineers World Congress, Detroit, 2001, number SAE 2001-01-0796.

Lee, P.S., Dexter, A. I. 2005. A fuzzy sensor for measuring the mixed air temperature in air-handling units, Measurement, Volume 37 (1): page 83–93.

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