INTERNATIONAL JOURNAL OF REFRIGERATION 63 (2016) 225–236

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/ijrefrig

A general method for calculating the uncertainty of virtual sensors for packaged air conditioners

Howard Cheung [a,*], James E. Braun [b]

[a] Department of Building Services Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong
[b] Ray W. Herrick Laboratories, Purdue University, West Lafayette, Indiana, USA

ARTICLE INFO

Article history:
Received 6 February 2015
Received in revised form 19 June 2015
Accepted 28 June 2015
Available online 29 July 2015

Keywords:
Virtual sensor
Uncertainty
Leverage
Regression diagnostics
Packaged air conditioners

ABSTRACT

Virtual sensors use data from low-cost measurements and calibrated models to provide outputs that would either be too expensive or impossible to measure directly. Virtual sensor technology has the potential to enable cost-effective implementation of advanced monitoring, diagnostic, and/or control features for buildings. While it is commonly known that the reliability of virtual sensors depends on the amount and conditions of calibration data, no methods have been presented that quantify the effect of the conditions of calibration data on virtual sensor output uncertainty. In this paper, a general method is presented for estimating the virtual sensor output uncertainty in terms of the uncertainty, conditions and amount of calibration data. The method is demonstrated with a power consumption virtual sensor for packaged air conditioning systems.

Une méthode générale pour calculer l'incertitude des capteurs virtuels de conditionneurs d'air compacts

Mots clés : Capteur virtuel ; Incertitude ; Influence ; Diagnostic de régression ; Conditionneurs d'air compacts

1. Introduction

Packaged air conditioning units, such as rooftop units (RTUs), provide cooling for over 40% of the air-conditioned floor space in commercial buildings in the United States (EIA, 2003). Furthermore, space cooling is responsible for over 14% of the total primary energy use in commercial buildings in DOE (2007). As a result, new technologies that can improve the overall operational efficiency of RTUs, such as advanced diagnostics or optimal control, have received increasing attention. However, some of the techniques require expensive measurements such as power and capacity, which has hindered their widespread adoption. To reduce the cost of the measurement, virtual sensors for RTUs have been proposed and evaluated.

---

* *Corresponding author.* Department of Building Services Engineering, The Hong Kong Polytechnic University, Room ZS813, Hung Hom, Kowloon, Hong Kong. Tel.: +852 2766 5994.
E-mail address: howard.at@gmail.com (H. Cheung).

http://dx.doi.org/10.1016/j.ijrefrig.2015.06.022

Nomenclature

c_p	specific heat at constant pressure [kJ kg^{-1} K^{-1}]
c_v	specific heat at constant volume [kJ kg^{-1} K^{-1}]
E	energy consumption [kWh]
$\mathbf{H}$	Hessian matrix [varies]
J	Jacobian matrix [varies]
k	specific heat ratio
m	number of coefficients
n	number of data points
P	pressure [kPa]
T	temperature [K]
$t_{DOF,1-\alpha}$	t statistics under a confidence interval 100(1 – α)% and a degree of freedom DOF
$\dot{W}$	power consumption [kW]
$\vec{x}$	input vector [varies]
$\bar{x}$	sample mean [varies]
x_{ij}	the entry in the ith row and jth column of matrix **X**
$\vec{y}$	output vector [varies]
$\hat{y}$	predicted value of variable y at a single data point [varies]

Greek

β	coefficients [varies]
γ	Jacobian leverage [varies]
Δx	uncertainty of variable x [varies]
ε	random error [varies]
θ	objective function [kW^2]
μ	population mean [varies]
σ_x	sample standard deviation of variable x [varies]
σ_{yx}	mean square error of predicted variable of y at input x [varies]
τ	time [h]

Subscript

comp	compressor
comp + cond	compressor and condenser fan
cond	condenser return bend
cov	model covariance
dev	output deviation
evap	evaporator inlet/evaporator fan
ideal input	without input uncertainty
in	inlet
input	input
out	outlet
output	output
overall	overall
train	calibration data
v	saturated vapor

Virtual sensing technology estimates some system quantity of interest using a regression model and low-cost measurements. A variety of virtual sensors have been developed in recent years for different HVAC equipment to replace measurements that are either expensive or impossible to measure directly. For instance, airflow rate can be measured directly with hot wire anemometry but it is too expensive for widespread application. On the other hand, a virtual air flow sensor could employ a fan-motor characteristic along with a differential pressure measurement as an input. In a general sense, a virtual sensor uses a regression model to predict the required output quantity using inexpensive sensors to provide the necessary inputs.

Li et al. (2011) gave an extensive review of different types of virtual sensors that included virtual refrigerant charge, refrigerant pressure, virtual refrigerant flow rate, and virtual compressor power consumption sensors for vapor compression equipment. Recent developments can also be found in Yu et al. (2011a, 2011b) for virtual supply air temperature and airflow sensors for RTUs, in Song et al. (2012) for virtual water flow rate measurement, in Zhao et al. (2012) for a virtual condenser fouling sensor and in Kim and Braun (2012) for improved virtual refrigerant charge sensors.

All physical measurements require specification of accuracy and uncertainty, and virtual sensors should also meet this requirement. Song et al. (2012) and Yu et al. (2011b) discussed how measurement uncertainties in inputs to virtual sensors propagate to their outputs. Song et al. (2011) considered how the uncertainty due to the mean squared error of the regression model and the uncertainty from calibration data in the regression process affect the uncertainty of the virtual sensor output. However, the effects of the uncertainty of the regression model on the virtual sensor output were not considered. In addition, existing uncertainty calculation methods only estimate uncertainty between virtual sensor predictions and values obtained by direct measurement of the predicted variable. These uncertainties are not directly comparable with those of the direct measurements because they are not referenced to the true values of the quantities.

In this paper, an uncertainty calculation approach is developed and demonstrated that can estimate virtual sensor uncertainties relative to true values so that overall virtual sensors can be evaluated in terms of accuracy and cost relative to direct measurement approaches. The method considers the uncertainty due to time fluctuation of sensor readings, the uncertainty of the physical sensors, and the uncertainty due to the regression process. Results are presented for virtual power sensors that were calibrated using field data from 3 RTUs and the dominant sources of uncertainty are identified for a variety of conditions.

This paper is divided into development and application sections. Section 2 develops a generalized virtual sensor output uncertainty approach, whereas Section 3 applies the general approach for evaluating the uncertainty associated with virtual power sensors for RTUs. The application includes demonstration results using field data from three RTUs.

2. Virtual sensor output uncertainty development

An output of a virtual sensor should be an unbiased estimator of the true value of the quantity. Its uncertainty describes