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Virtual in-situ calibration method in building systems

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ABSTRACT

Sensors play an important role in guiding building systems to achieve desired operation and efficiency. However, sensors are subject to continuous degradation and failures over time. Although a periodical calibration is needed, it is exceptionally difficult and/or impractical to many sensors with a conventional manual approach. Uncalibrated problematic sensors could significantly compromise the systems' performance and lead to unintended loss of energy efficiency in buildings. We propose a methodology, termed virtual in-situ calibration, to solve this critical issue. It is developed by mathematically extracting the characteristics of essential aspects involved in a calibration, including the environment assessment, benchmark establishment, and uncertainty quantification. A case study of a supply air temperature sensor in rooftop units illustrates the implementation process; the erratic uncertainty is reduced from ± 19.2 °C to ± 0.7 °C after the virtual in-situ calibration. The calibration method can be implemented online to significantly improve the reliability of sensor networks in buildings.

1. Introduction

In modern buildings, heating, ventilation, and air conditioning systems (HVAC) consume a significant amount of energy in order to offset the thermal load and provide an acceptable indoor environment to occupants [1,2]. Due to the magnitude of energy use associated with HVAC systems, continuous monitoring, analysis, and optimization of HVAC systems are of central importance to ensure the overall operational efficiency of buildings. It allows the identification and correction of undesired actions of various devices deployed in buildings that, if malfunctioning, may lead to excessive energy use. Due to the large quantity and complexity of devices in central HVAC systems, this process can barely be handled manually; instead, it is fulfilled automatically with an enhanced building automation system (BAS) that electronically integrates the mechanical devices through sensing, computing, data processing, and actuating. Associated with the decision-making process, reliable and adequate measurements from sensors/meters on the components and systems are of great priority and importance in maintaining the performance of BAS and energy saving protocols. However, due to the consideration on initial cost, building systems are generally under-sensed with near-zero sensor redundancy. Physical variables of our interest in HVAC systems and buildings may be measured with only one sensor or even not measured. For example, the outdoor intake ratio in air-handling units is seldom acquired. Meanwhile, many sensors in building HVAC systems are improperly installed, wrongly placed, damaged, or gradually failed in the adverse working environment [3,4]. Readings from these sensors or transmitters could be inaccurate or totally wrong. Because of zero redundancy in typical building systems, it becomes difficult to tell the reliability and accuracy of measurements. Using erroneous data or wrong information could lead to a significant energy penalty or even direct failure of control and operation algorithms.

Sensor errors generally comprise precision degradation, reading bias, drifts, noise, or sensor failure. Conventional approaches for correcting the errors and improving the accuracy of measurements from various sensors and meters in real buildings can be categorized as (1) sensor calibration [5–7] and (2) statistics-driven data fusion [8–10]. The essence of a physical sensor calibration is a well-designed comparison against a standard instrument in a predefined environment to bring the working sensor back to its normal condition. A sensor calibration is the fundamental method of correcting suspicious sensors. Generally, all sensors in a dynamic system should be checked regularly against standard instruments to ensure measurements' quality. For example, for temperature measurements, sensors should be calibrated every 12 months; for pressure gauges, calibration is desired every six months [5]. In addition to the sensor calibration, statistic data fusion methods may also be applied to obtain the representative value of physical variables. With a data-driven method, different data or information sources (for instance, direct measurements from physical sensors and indirect measurements from models) are integrated in a data fusing process to obtain accurate, complete, or dependable information [e.g. 8,9]. The main procedure of data-driven methods consists of various filtering algorithms and statistical processes.

A sensor calibration is preferred over a data fusion method since the former works frontend on a sensor itself for maintaining the quality of

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Nomenclature

Abbreviations

AFDD	automated fault detection and diagnostics
HVAC	heating ventilation and air-conditioning
Th	threshold
SAT	supply air temperature
MAT	mixed air temperature

Symbols

f	function for calibration
g	mapping function
m	sample size or counter of timestamps
p	size of samples
q	input for a dependent measurement
t	T-distribution variable
u	standard uncertainty
v	variable
x	measurement instance
y	measurement or benchmark from the reference sensor or virtually established benchmark
z	variable
J	cost function
N	number of benchmarks
S	standard deviation
V	vector of variables v
X	vector of measurements from sensors
Y	collection vector of benchmarks
Z	vector of variables z
$\overline{X}$	vector of mean values of measurements
$\overline{Y}$	vector of mean benchmark values
α	confidence internal
v	specific volume of air
μ	expected average of the population
$\sigma_{\overline{X}}^2$	variance of the samples
σ^2	variance of the population
c_p	specific heat
H_{stage}	heating stage command
OAD_{st}	outdoor air damper set-point
Q	dependent measurement
$\dot{Q}_H$	heating capacity
SAT_c	supply air temperature after calibration
SAT_{meas}	reading from the physical sensor
U_f	combined uncertainty
$\dot{V}_{means}$	measured supply air flow rate
ΔT_{fan}	supply fan temperature rise.

Subscripts

bi	counter for benchmarks
c	corrected measurements after calibration
h, i, j, k	general counter
M	counter for measurements
reading	Reading from an additional instrument
si	counter for sensors
signal	signal from a sensor
steady	steady state condition
uniform	uniform condition

direct measurements. Meanwhile, a calibration is the most effective method in reducing systematic errors and eliminating failure of sensors. Despite the necessity, a sensor calibration is scarcely carried out regularly on various sensors in building HVAC systems unless significant measurement errors or malfunctions are identified. The main challenges to conduct a regular calibration on sensors are as follows:

1. *Time and monetary cost.* A complete calibration process of an individual sensor includes multiple steps, from removing a working sensor from a system, conducting a calibration, to reinstalling it; any of the steps could be time consuming and expensive.
2. *Disruption to a normal operation.* Removing and reinstalling a sensor will more or less disrupt the normal operation of HVAC systems. Missing measurements from the removed sensor also need to be covered temporarily to resume the operation during the process.
3. *Access to various sensors.* Due to the space and installation constraints, it could be impractical or very costly to remove some sensors (e.g. a flow rate meter in a pipeline, a temperature sensor hiding behind the ceiling) from its working environment.
4. *Large quantity of sensors.* Building HVAC systems have a large sensor network to acquire different types of information (e.g. temperature, humidity, flow rate, CO_2, etc.) from different levels on the operation of the system. This factor further amplifies the difficulties listed above.

In addition to these challenges, there is one more limitation directly associated with a conventional calibration. A physical sensor after calibration may not have a favorable working environment as in a calibration to function properly and provide a close measurement to the real value. For example, Yu. et al. [11] found that the commonly preinstalled supply air temperature sensor in compact rooftop air-conditioners cannot accurately measure the real temperature of supply air. Due to the compact size, poor air distribution, and intensive thermal radiation of gas heating chamber, errors associated with the sensor could be erratic and up to 19.2°.

In addition to acquiring improved accuracy and resiliency against errors, an ideal calibration process should be conducted as in-situ, hence avoiding the differences in the medium and changes of working environment and the associated effects on the measurements. In this study, we present an innovative virtual in-situ calibration algorithm, which is non-invasive, real-time, and can be potentially automated to handle the aforementioned challenges and limitations of a conventional calibration. In the following article, additional background knowledge on a conventional sensor calibration is provided. Next, the related work of sensor calibration methods in other fields is reviewed. The methodology is then described and the mathematical framework of the virtual in-situ calibration is formulated. The article concludes with a case study and discussions.

2. Conventional calibration and application on typical sensors

2.1. Conventional calibration

Generally, a measurement is only an approximation of the "true" value of a measurand. Because of the involved errors, i.e. systematic errors and random errors, such a measurement should always be accompanied by a statement of uncertainty [12]. Measurement quality, which defines our knowledge about factors that lead to the difference between a measurement and a measurand, can only be maintained with confidence through a calibration process. Conventionally, a calibration refers to "*the set of operations that establish, under specified conditions, the relationship between values of quantities indicated by a measuring instrument, a measuring system or values represented by a material measure, and the corresponding known values of a measurand*" [13]. Essentially, a calibration is a comparison and correction process. Standards are needed in the process as "*a material measure or physical property that defines or reproduces the unit of measurement of a base or derived quantity*" [12]. They refer to the known values of a measurand in given scenarios. For different accuracy and applications, different levels of standards are used, including fundamental or absolute standards, international standards, national or primary standards,