ORNL/LTR-2020/1

Review: Sensor Impact on Building Controls and Automatic Fault Detection and Diagnosis (AFDD)

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January 2020

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE US DEPARTMENT OF ENERGY

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Energy and Transportation Science Division

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managed by
UT-BATTELLE, LLC
for the
US DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

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FIGURES

1. INTRODUCTION

This report summarizes a literature review as a Q1 deliverable of the "Sensor Impact Evaluation and Verification" project.

This project's overarching goal is to develop a framework for investigating the impact of sensor deployment and configuration for building energy optimization, fault detection and diagnosis (FDD), occupants' thermal comfort, and potential grid efficiency. The proposed project flow is shown in Figure 1.

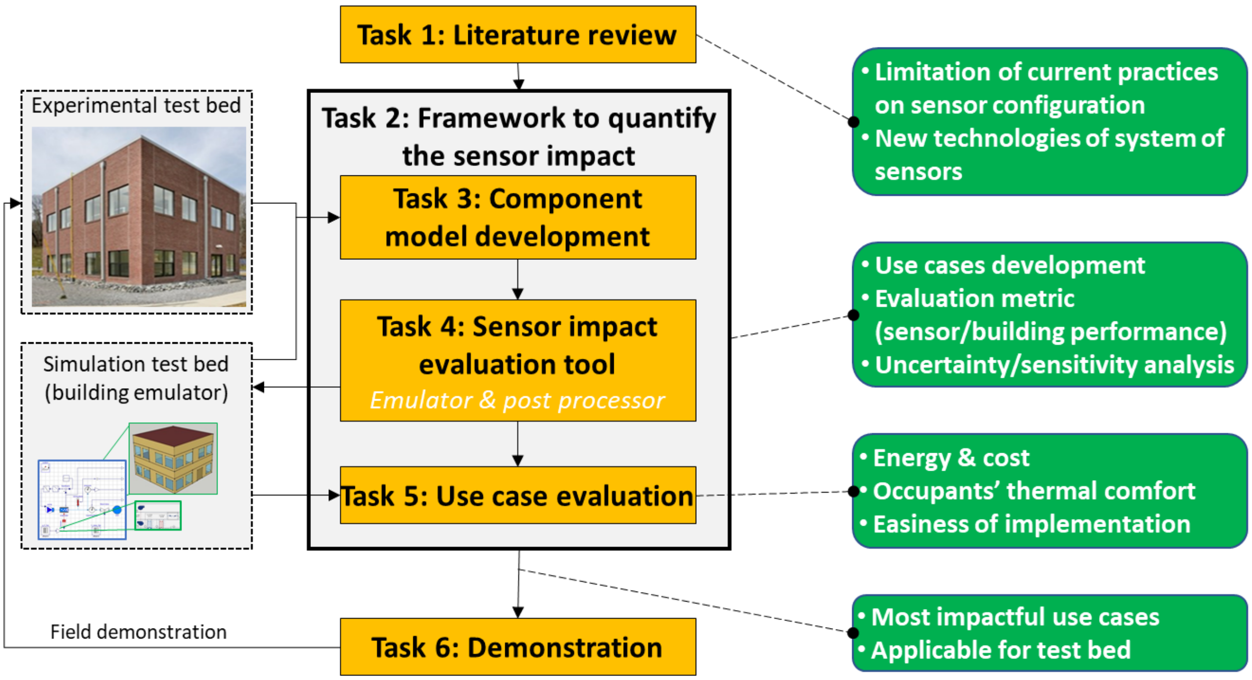

Figure 1: Schematic flow of the project.

The project's first task was a literature review, which established a solid knowledge of and a background related to sensor technologies and placement. To accomplish this, an extensive literature review of previous research and a survey of current industry practices were performed. The literature review of sensor technologies and placement was expected to contribute to (1) understanding the previous and current research, (2) identifying research gaps in current and previous work, and (3) investigating the potential impacts on building performance.

During Q1, the multi-lab team reviewed 65 research papers, technical reports, and related books to identify the current methods of sensor selection and placement. This report categorizes the review work for building controls and automatic FDD and summarizes the main findings. In Q2, the team will continue the literature review for building controls and FDD based on selected sensor suites. The team will also conduct a series of interviews and/or surveys to further investigate the current status and limitations of sensor configuration.

2. LITERATURE REVIEW

During the literature review, the team categorized the literature by topic (i.e., control-related or FDD related), research methodology (i.e., simulation, experiment, review, or guideline), priority (i.e., 1, 2, 3, or 4), building type (i.e., residential or commercial), and system layer (i.e., room, heating, ventilation, and air conditioning (HVAC), or building), as shown in Figure 2.

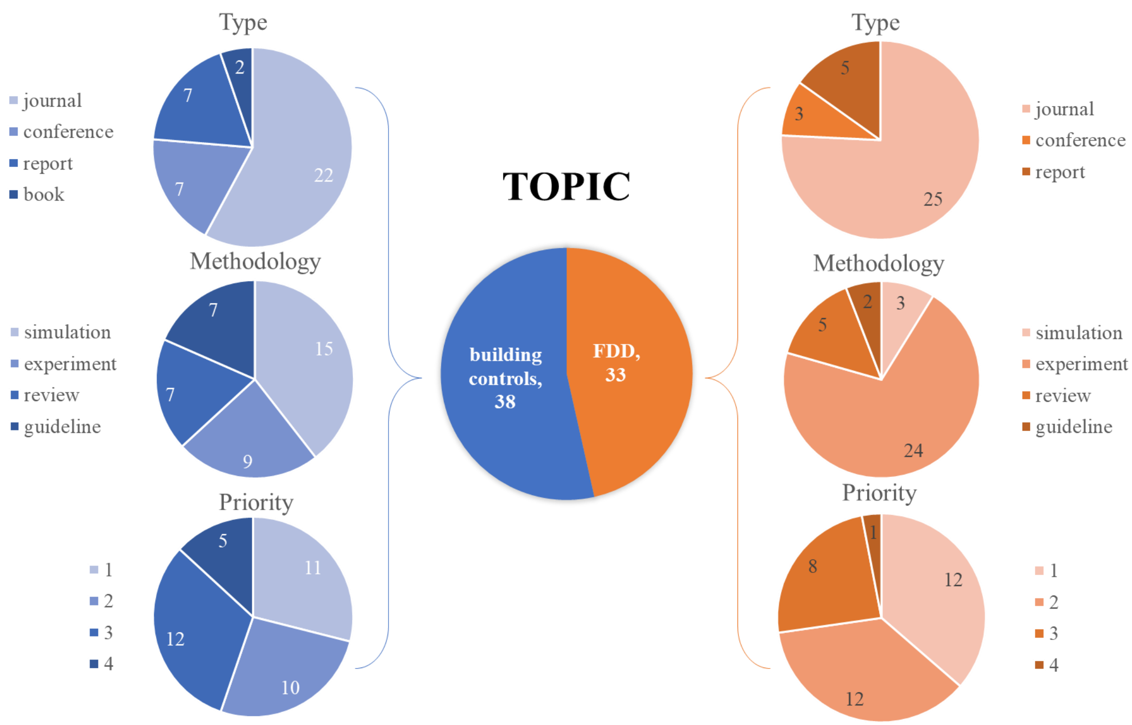

Figure 2: Categorized review work for building controls and FDD by type, methodology, and priority.

The review work methodologies were also categorized for building controls and FDD, as shown in Figure 2. Some references could be classified into multiple categories. For example, if research was performed for both simulation study and experimental study, then the reference was categorized into both simulation and experimental study.

The literature's priority was set by examining the main theme and topic, methodology, and application, as shown in Figure 2. If the main topic of the literature was closely aligned with the project goal, then priority 1 was assigned. If the literature contained useful information, such as a rule, practice, or norm in terms of the sensor design or configuration, then priority 2 was assigned. If any useful information was found, including a keyword, definition, methodology, term, or related application, then priority 3 was assigned. If useful information was hardly found, or it was off-topic, then priority 4 was assigned.

Journal papers were a main source for the literature review, followed by conference papers and reports. For the building controls-focused review, 40% were simulation studies and 30% were experimental studies, whereas the FDD-focused literature reviews were 70% experimental studies. In the priority categorization, 60% were priority 1 and 2 for building controls-focused reviews, and 75% were priority 1 and 2 for FDD reviews.

The review work was also categorized by building type and system layer, as shown in Figure 3. Few studies were found to have been performed in the residential building sector (i.e., 20% for building controls research and 8% for FDD research). In the system layer classification, most FDD works were confined to the HVAC layer, whereas the room and HVAC layer were more than 87% in the building controls works.

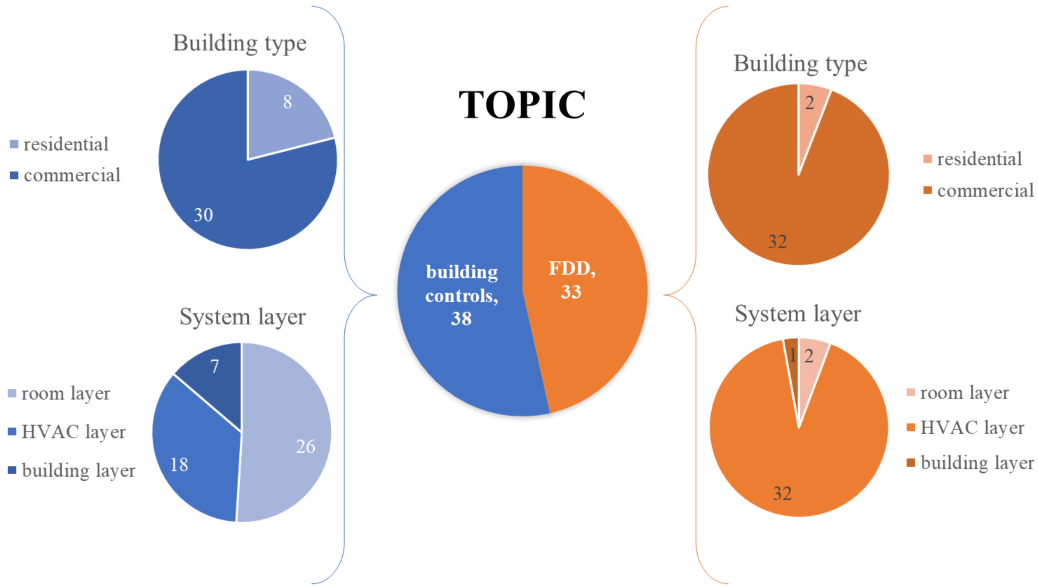

Figure 3: Categorized review work for building controls and FDD by building type and system layer.

3. MAIN FINDINGS

This section describes the literature review summary and the main findings of the sensor impacts on building controls and FDD.

3.1. Sensor Impact on Building Controls

- **Most studies focused on applications in commercial or public buildings.**

  Most papers and reports focused on experiment and simulation study in commercial buildings and public buildings (e.g., offices, retail, hotels, hospitals, classrooms, libraries, study areas). Only a few research papers focused on residential buildings as reference building targets [8, 13, 29, 34].

- **Most sensors investigated in building controls included the sensors for the room layer and building layer.**

  Frequently investigated sensors in the literature can be summarized as follows.

  - Room layer (e.g., thermostat [3, 15, 18, 37, 39], occupancy sensor [3, 11, 13], CO_2 sensor [3, 6, 13, 20], volatile organic compound sensor, lighting sensor [2, 3, 12])
  - HVAC layer (e.g., temperature sensor [2, 35], air flow meter [9, 12], static pressure sensor [15])
  - Building layer (e.g., total energy consumptions, power meter [3, 5, 8])

- **Sensor requirements and configurations are normally from codes, standards, and reports. Applications in variable air volume (VAV) systems are a key research subject.**

  Important standards and codes (e.g., Sensor Characteristics Reference Guide [PNNL-22484]; ASHRAE Standards 90.1, 90.2, 55, 62.1, and 189.1; International Energy Conservation Code; International Building Code; National Fire Protection Association 5000 code) are foundations that support multiple types of sensors (e.g., HVAC, room, and building sensors) used in building subsystems that facilitate energy efficiency and cost savings [41]. These codes provide sensor locations and configuration requirements for a wide range of application scenarios, such as occupancy-based HVAC and lighting control, FDD, commissioning, indoor air quality control, ventilation, transactive energy, and renewable integration. A report by Kuruganti et al. introduced the gaps in sensor applications in building control and FDD research areas [42]. The potential sensor technologies and configurations proposed as solutions for different application examples are also provided in this report [42]. For example, low-cost, self-powered wireless sensors could be applied for fault detection in a large building in which it is costly to have multiple traditional temperature sensors. For the VAV system, the sensor requirements for different control strategies based on ASHRAE handbooks are proposed in Taylor et al. [10]. For example, a discharge air temperature sensor (an HVAC layer sensor) is needed in most cases. Extensive design information for HVAC layer sensors in the VAV system in commercial buildings [2] was introduced, including the recommended VAV minimum position (normally ~30–50%) and VAV control methods. The effect of sensor placement location on VAV system performance in terms of indoor thermal comfort (Predicted Mean Vote, PMV) and energy consumption was analyzed in Du et al. [35].

- **Many studies investigated the optimization of sensor placement and the number of sensors in the HVAC layer and room layer for improving building energy performance and indoor thermal comfort.**

  Sensor locations and the number of sensors are generally selected based on engineering judgment or heuristic methods [28]. In previous studies, efforts were made to investigate how sensor locations affect building performance. Many studies used computational fluid dynamics (CFD) modeling or CFD/Modelica coupling. Tian et al. [18] optimized the locations of room layer sensors to maximize indoor thermal comfort (PMV) using CFD and Modelica. Bianco and Tisato [11] optimized the location of vision sensors to detect occupancy. The impact of different sensor types on HVAC system performance was also considered in recent studies. Liu et al. [15] suggested a method for optimizing sensor placement to reduce HVAC energy consumption. The space dimensions and sensor specifications, types, and locations were used as the inputs for optimization. Painter et al. [6] proposed a method to support building control commissioning and maintenance by providing higher resolution data and speeding up the commissioning process. Yoganathan et al. [38] used a clustering algorithm to determine optimal sensor coverage in an office building. Chen et al. [22] proposed a method for reducing the number of installed room layer sensors by developing virtual sensors that combine the prior knowledge of temperature statistics and Bayesian Model Fusion.

- **Optimized sensor location and displacement and their impact on building systems must be investigated thoroughly.**

  The optimal number and location of sensors vary with sensor type. A separate sensor node, rather than a multi-sensor system, could be needed for optimality. Also, the optimal spatial location of temperature and humidity sensors could vary slightly with time [38]. The majority of the sensors in the building space might require optimization for their location/displacement to realize a considerable impact on system-level energy consumption. In a study by Du et al. [35], changing the sensor positions in one of the building's seven rooms resulted in an HVAC energy variation between -0.34 to 0.14% only. Therefore, a sensor placement retrofit in a small subset of the building might not affect the overall HVAC energy consumption (air side + water side).

  Placing a temperature sensor for the VAV control loop at the return air inlet is not always the optimal solution [35]. During the cooling season, the required airflow increases when the sensor is placed at the return air duct [54] since the temperature in the return duct is usually higher than the zone temperature, which can lead to overcooling. The required supply airflow rate depends on how close the temperature sensor [35] is to the supply air diffuser versus the occupant and internal heat gain sources. Indoor thermal comfort (PMV) is most satisfied and energy usage is lower when the sensor is placed away from the return air inlet, the supply air outlet, or a heat source. When the room-level temperature sensor is placed near the diffuser [37], the required fan power is reduced, but the return air is warmer, resulting in a large cooling load and increasing chiller plant power consumption.

- **A few studies estimated the energy-savings potential of deploying various sensors and controls.**

  Using advanced thermostats, such as occupancy-based wireless thermostats and learning thermostats ($150–330/thermostat), can save energy in office buildings by reducing HVAC energy consumption by ~5–30% [3]. CO_2 demand-controlled ventilation can achieve heating and cooling energy savings of up to 10% compared with typical building system designs. The initial system cost (~$1–3/cfm/system) would vary by design and outdoor air requirements, which are determined by occupancy and floor area. Advanced controls based on additional sensor deployment could also save energy. By replacing a conventional system with an advanced rooftop controller (~$2,000–4,000/ roof top unit, RTU) that enables economizing controls that use temperature sensors or real-time weather data, HVAC energy consumption can be reduced by up to 40%. Implementing advanced control strategies (e.g., using optimal setpoint control [63] or model predictive control strategies [64, 65]) can achieve cooling energy savings of up to 40%. A tenant comfort feedback system or a cloud-based energy management information system can also achieve HVAC energy savings of ~15–25%.

- **Optimal selection and placement of certain sensors can improve thermal comfort.**

  Optimal placement of thermostats can significantly improve occupants' comfort, but this could result in additional energy usage. An HVAC energy consumption increase of ~8% was reported in a study that diagnosed and corrected poor comfort conditions by relocating thermostats in a restaurant equipped with multiple rooftop units [37].

  Adding additional zones could also improve thermal comfort. Although adding zones could increase the cost of the mechanical systems by $3–6/ft^2, an uncomfortable indoor environment could lead to operating personal space heaters and fans, which would consume more energy. Instead, sub-zoning with self-powered VAV diffusers can be a reasonably lower cost option, with an additional cost of ~$200–250 per diffuser [3].

- **Wireless sensor systems could reduce installation and integration costs in retrofit applications.**

  Wireless sensor systems offer cost benefits and improved flexibility for retrofit applications. A 10–15% reduction in installation cost was achieved with a wireless sensor network-based building HVAC control system compared with a conventional wired system [53]. Standalone devices might be more cost-effective than wireless sensors, but the resolution is not as great as expected. Integrating the existing sensor data and additionally installed sensors could be a challenge [6]

  For the initial cost, the ownership structure for the cost should be considered [3], and sensor sets can be reused multiple times in different buildings for the commissioning process [6].

3.2. Sensor Impact on FDD

- **Current FDD research focuses more on FDD algorithms than sensors.**

  Data-driven (or history-based) FDD models account for 62% of FDD models from 197 research papers since 2004 [32]. The rapid development of machine-learning techniques empowers data-driven FDD models with good performance and high reliability. Data-driven FDD models with sophisticated machine-learning algorithms are hungry for data. They require higher data quantity, quality, and variety, and improved support from a sensor perspective is greatly needed.

Many studies applied very sophisticated machine-learning algorithms with existing sensors that are common to building automation systems. They focused more on the algorithm than the sensors. There is a gap between fast-developing FDD algorithms and a lack of support from a sensor perspective.

- **Sensor selection, sensor faults, and virtual sensors are the main FDD study topics related to sensors.**

Many studies discussed the sensor selection problem in FDD modeling. Sensor selection is a widely discussed topic in FDD for chillers [43, 47, 51], variable refrigerant flow systems [48], air handling units [49], and whole HVAC systems [45]. These sensor selection studies focused on selecting the sensor set used for FDD from existing sensors to improve FDD performance rather than installing new sensors. Sensor selection is widely studied, but sensor replacement is not; there are large opportunities for the future study of sensor replacement in FDD application.

Many studies focused on sensor faults in building HVAC systems [46, 56, 57]. Sensor faults greatly affect building energy efficiency [58] and have been identified as an important fault type in existing FDD studies.

The virtual sensor is also an important topic in FDD research [50, 52, 59]. Virtual sensing systems use the information available from other sensors and process parameters to calculate an estimate of the quantity of interest. Like sensor selection studies, virtual sensor technique research uses existing sensors instead of installing new sensors.

Other research topics, such as sensor location and distribution for FDD [59], the minimum number of required sensors for FDD [60], and low-cost sensors for FDD [61], exist but are not very widely discussed.

- **Most FDD studies used existing sensor systems in buildings; very few studies focused on sensor design as an integral aspect of FDD development.**

Very few studies addressed sensor design as part of FDD development. Some studies used simulation tools such as EnergyPlus and Modelica to simulate faults [62]. Since simulation tools have thousands of "virtual sensors," they can be used to decide which sensors are important for FDD, or they can apply sensor selection before the sensors are physically installed. Most FDD research is based on existing sensor systems in buildings. Tailoring sensor design and configuration to FDD algorithms is expected to substantially improve FDD performance.

4. SUMMARY AND FUTURE WORK

The impact of sensor deployment and configuration for building energy optimization, FDD, and occupants' thermal comfort was investigated through an extensive literature review. The literature review on sensor selection and sensor placement contributed to (1) understanding the previous and current research, (2) identifying research gaps in the current and previous work, and (3) investigating the potential effects on building performance.

4.1. Sensor Impacts on Building Controls

- Most studies focused on applications in commercial or public buildings.
- Most sensors investigated in building controls included the sensors for the room layer and building layer.
- Sensor requirements and configurations are normally from codes, standards, and reports. Applications in VAV systems are a key research subject.
- Many studies investigated the optimization of sensor placement and the number of sensors in the HVAC layer and room layer for improving building energy performance and indoor thermal comfort.
- Optimized sensor location and displacement and their impact on building systems must be investigated thoroughly.
- A few studies estimated the energy-saving potential of deploying various sensors and controls.
- Optimal selection and placement of certain sensors can improve thermal comfort.
- Wireless sensor systems could reduce installation and integration costs in retrofit applications.

4.2. Sensor Impacts on FDD

- Current FDD research focuses more on FDD algorithms than sensors.
- Sensor selection, sensor faults, and virtual sensors are the main FDD study topics related to sensors.
- Most FDD studies used existing sensor systems in buildings; very few studies focused on sensor design as an integral aspect of FDD development.

To further understand current practices and to investigate the application of interest for sensor impact research, surveys and/or interviews will be performed. The literature review, as well as survey/interview results, will be documented in a journal paper (Q2 deliverable). The findings from the literature review and survey will also be used to define high-priority use cases, define evaluation metrics, and develop a framework for quantifying the sensor impact.

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