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# Diagnosis of sensor grids in a building system using BRIDGE approach

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**Abstract**—This paper aims at designing a diagnosis tool for detecting and localizing faults in a building system. A Bridge approach based diagnostic reasoning is used because it proves to be more relevant to provide the possible fault modes including multiple sensor faults. The efficiency of this method is illustrated by an example.

**Index Terms**—BRIDGE approach, sensor grids, test design, fault diagnosis, building system

## I. INTRODUCTION

Performing diagnoses count on a complex process, which is decomposed in 2 steps: a design process and a running process. The following design tasks may be distinguished: system modeling, sensor placement, detection test design and isolation algorithm design. The system modeling task aims at formalizing the reference behaviors. In general, reference behaviors are modeled by constraints that establish the relationships between data coming from observations and unknown variables. Each constraint models one or several behavioral modes. In AI community, a system modeling task is detailed in [2] and [12]. Each system's element can take 2 modes: the ok mode, denoted  $ok(\text{component})$  in [5], which represent the normal behavior of a component and its complementary mode, named unknown fault mode in [5], [13]. It's named  $cfm(\text{component})$ . Modeling task is to formalize the constraints that model the different modes of the system to be diagnosed.

The design of detection tests is usually not explicit in AI approaches: Tests are always designed by checking the consistence between the constraints and the data. But, FDI community's results ([1], [4]) indicate that a detection test can not be given from a simple comparaison between the system description's element and observations. Thus, get together the works of FDI and AI community has been made in order to make a bridge between FDI and AI results ([3], [10]). As a result, detection test design tasks can be decomposed in to the two following sub tasks: the generation of testable subsystem and the detection

algorithm: the first one selects subsets of constraints that may lead to detection tests[1], the second one consists in designing a detection test, often named Analytical Redundancy Relation, corresponding to each testable subset of constraints.

The task of designing isolation algorithm consists in selecting the most relevant diagnostic analysis approach. In order to analyse the symptoms generated by detection tests, different approaches like decision tree based approach ([9], [11]), case based reasoning approach ([6], [8]) or the signature based approach [1] are proposed in the litterature. In this work, we consider the bridge approach [10]. It has been proved that we can use consistency based reasoning to analyze symptoms coming from detection tests characterized by the involved modes.

The paper focuses on a real case of study: an office in Grenoble Institute of Technology, where 3 persons work. It is equipped with 27 sensors which collect information about CO2 concentration, temperature, occupancy ... In addition, it is also equipped with 2 cameras to verify the actions and routines of occupants. Fig.1 show the test bench.

This paper is organized as follow: section 2 presents the problem statement. In section 3, the physical model of the office is exposed. Section 4 is devoted to the design of tests. To assess the validity of the proposed approach, experimental validation is presented in section 5. Finally, concluding remarks are given in section 6.

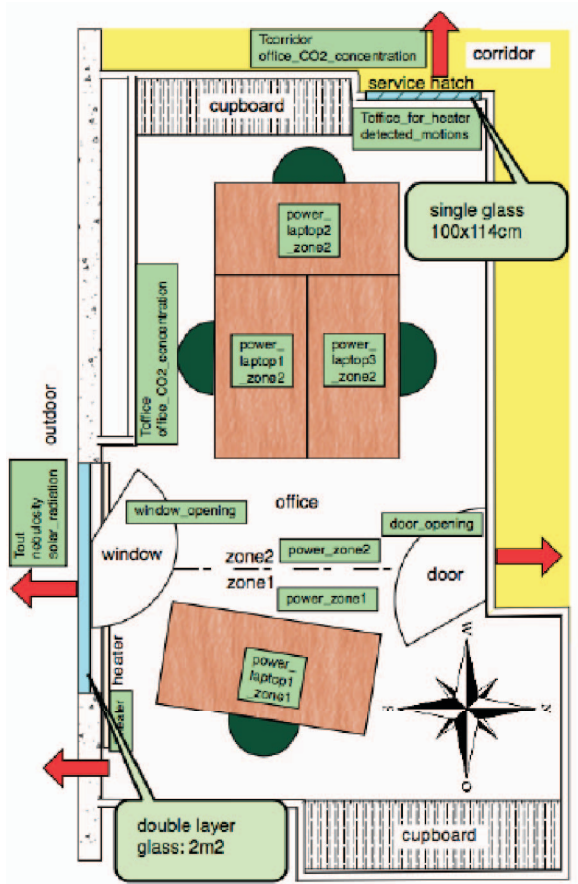


Fig. 1: Test bench

## II. PROBLEM STATEMENT

### A. Design of detection tests

The design of detection tests is the first step of a diagnostic process. Detection tests are designed to reveal the faulty behavior in the sensor grids. They are derived from simple sensor measurements and uses the method of bound check to decide whether a subsystem is faulty or not. Bridge diagnosis process starts with a negative test. Using this approach, we analyse an office with about 30 sensors to determine whether the sensor has normal behavior or not. Each sensor represents the normal behavior and abnormality leads at least to one fault. The proposed approach focuses on performing detection tests to data sets and find the fault modes ( $ok(\text{sensor } 1), \dots, ok(\text{sensor } n)$ ) by applying the new approach to diagnosis.

### B. Symptom generation

The symptom generation is the second task of a diagnostic process. Symptoms are generated thanks to a threshold of residuals.

The value of threshold is related to the distance between two sensors involved in the test. Thus, residual value is the hourly average value of the difference between the amount of data collected from two sensors. If the value

of the residue is higher than the given threshold value, a symptom is generated.

The behavior of the building is dependent of the season, a period of validation from May 1st, 2015 to June 30th, 2015 is chosen.

## III. PHYSICAL MODEL

Advanced energy management systems rely on physical models. For example, to predict the inside temperature for the office, the following physical model is used:

TABLE I: Physical parameters

Parameter	Designation
$T_n$	the temperature of the neighbor corridor
$T_{in}$	the temperature of the office
$T_{out}$	the outdoor temperature
$R_n$	the thermal resistances of the wall separating the office from the corridor
$R_{out}$	the thermal resistances of the wall separating the office from the outdoor
$R_D$	the thermal resistances of the door when he is closed
$R_W$	the thermal resistances of the window when he is closed
$\zeta_D$	the opening rates of the door
$\zeta_W$	the opening rates of the window
$R_i$	the resistance of walls
$C_i$	the capacity of walls
$\phi_{in}$	the internal thermal gains: solar gains, gains of electricals devices and gains due to the occupancy

$$\text{Let } \frac{1}{R} = \frac{1}{R_i} + \frac{1}{R_{out}} + \frac{\zeta_W}{R_W} + \frac{\zeta_D}{R_D} + \frac{1}{R_n}$$

$$R_D = \frac{1}{\rho_{air} C_{p,air} Q_D} \quad (1)$$

$$R_W = \frac{1}{\rho_{air} C_{p,air} Q_W} \quad (2)$$

$$ok(\text{room}) \rightarrow \frac{d\tau}{dt} = \frac{R - R_i}{R_i^2 C_i} \tau + \frac{R}{R_i C_i} \phi_{in} + \frac{R}{R_i C_i} \left( \frac{1}{R_{out}} + \frac{\zeta_w}{R_w} \right) T_{out} + \frac{R}{R_i C_i} \left( \frac{1}{R_n} + \frac{\zeta_D}{R_D} \right) T_n \quad (3)$$

$$ok(\text{room}) \rightarrow T_{in} = \frac{R}{R_i} \tau + R_i \phi_{in} + R \left( \frac{1}{R_{out}} + \frac{\zeta_w}{R_w} \right) T_{out} + R \left( \frac{1}{R_n} + \frac{\zeta_D}{R_D} \right) T_n \quad (4)$$

with  $R_n$ ,  $R_{out}$ ,  $R_i$  and  $C_i$  time invariant.

Equation (4) constitute a model for predicting the inside temperature. By observing the variables included in it, we can conclude that the indoor temperature depend on different phenomena like the different sources of heat inside the office, corridor and outdoor temperatures etc... Determining the air quality is usually done by measuring the CO2 concentration in the air. Eq. (5) shows the model of the air quality.

$C_{out}$ ,  $C_{cor}$  and  $C_{in}$  represent respectively the  $CO_2$  concentration of the outdoor, the corridor and the office.  $V$  and  $n$  represent respectively the volume of the office and the number of occupants.

$$V \frac{dC_{in}(t)}{dt} = -(Q_{out}(t) + Q_{cor}(t))C_{in}(t) + Q_{out}(t)C_{out} + Q_{cor}(t)C_{cor}(t) + S_{CO_2}n(t) \quad (5)$$

[7]

with

$$Q_{out}(t) = Q_0^{out}(t) + \zeta_W(t)Q_W \quad (6)$$

$$Q_{cor}(t) = Q_0^{cor}(t) + \zeta_D(t)Q_D \quad (7)$$

Then, it yields Eq. (8):

$$\begin{aligned} ok(\mathbf{room}) \rightarrow V \frac{dC_{in}(t)}{dt} = & -(Q_0^{out} + Q_0^{cor}\zeta_W(t)Q_W \\ & + \zeta_D(t)Q_D)C_{in}(t) + (Q_0^{out} + \zeta_W(t)Q_W)C_{out} \\ & + (Q_0^{cor} + \zeta_D(t)Q_D - \zeta_W(t)\zeta_D(t)Q_{WD})C_{cor}(t) + S_{CO_2}n(t) \end{aligned} \quad (8)$$

Sensors are modeled by a model which assumes that the actual value is equal to the measured value under the assumption that the sensor is working well.

Equations from Eq. (9) to Eq. (16) each represent the model for each sensor in the office.

$$\begin{aligned} ok(\mathbf{office\_reference\_temperature\_sensor}) \\ \rightarrow \tilde{T}_{\mathbf{office\_reference}} = T_{\mathbf{office\_reference}} \end{aligned} \quad (9)$$

$$\begin{aligned} ok(\mathbf{office\_wall\_temperature\_sensor}) \\ \rightarrow \tilde{T}_{\mathbf{office\_wall}} = T_{\mathbf{office\_wall}} \end{aligned} \quad (10)$$

$$\begin{aligned} ok(\mathbf{heater\_temperature\_sensor}) \\ \rightarrow \tilde{T}_{\mathbf{heater}} = T_{\mathbf{heater}} \end{aligned} \quad (11)$$

$$\begin{aligned} ok(\mathbf{corridor\_temperature\_sensor}) \\ \rightarrow \tilde{T}_{\mathbf{corridor}} = T_{\mathbf{corridor}} \end{aligned} \quad (12)$$

$$ok(CO_2\_concentration\_sensor) \rightarrow \tilde{CO}_2 = CO_2 \quad (13)$$

$$\begin{aligned} ok(\mathbf{corridor\_CO}_2\_concentration\_sensor) \\ \rightarrow \tilde{C}_{\mathbf{corridor}} = C_{\mathbf{corridor}} \end{aligned} \quad (14)$$

$$ok(\mathbf{door\_contact\_sensor}) \rightarrow \tilde{\zeta}_D = \zeta_D \quad (15)$$

$$ok(\mathbf{window\_contact\_sensor}) \rightarrow \tilde{\zeta}_W = \zeta_W \quad (16)$$

$$ok(\mathbf{occupancy\_sensor}) \rightarrow \mathbf{occupancy} = \mathbf{occupancy} \quad (17)$$

Note that the symbol  $\tilde{\cdot}$  is used to denote the measured value and  $ok(\mathbf{component})$  signifies normal behavior of the component.

#### IV. DESIGN OF TESTS

The following tests have been constituted in the framework of the office setting.

**Test1 - check the performance of Toffice-reference and Theater sensors**

ok (Toffice\_reference\_sensor)  $\rightarrow$  Toffice= $\tilde{T}$ office-reference  
ok (Theater\_sensor)  $\rightarrow$  Toffice= $\tilde{T}$ heater

**Test2 - check the performance of Toffice-wall and Toffice-reference sensors**

ok (Toffice\_wall\_sensor)  $\rightarrow$  Toffice= $\tilde{T}$ office-wall  
ok (Toffice\_reference\_sensor)  $\rightarrow$  Toffice= $\tilde{T}$ office-reference

**Test3 - check the performance of door-contact sensor, window-contact sensor, Toffice-reference sensor and the validity of the model (ok(room))**

ok (Toffice\_reference\_sensor)  $\rightarrow$  Toffice= $\tilde{T}$ office-reference  
ok (door\_contact\_sensor)  $\rightarrow$   $\zeta_D = \tilde{\zeta}_D$   
ok (window\_contact\_sensor)  $\rightarrow$   $\zeta_W = \tilde{\zeta}_W$   
ok(room)  $\rightarrow \frac{d\tau}{dt} = \frac{R-R_i}{R_i^2 C_i} \tau + \frac{R}{R_i C_i} \phi_{in} + \frac{R}{R_i C_i} (\frac{1}{R_{out}} + \frac{\zeta_w}{R_w}) T_{out} + \frac{R}{R_i C_i} (\frac{1}{R_n} + \frac{\zeta_D}{R_D}) T_n$   
ok(room)  $\rightarrow T_{in} = \frac{R}{R_i} \tau + R_i \phi_{in} + R (\frac{1}{R_{out}} + \frac{\zeta_w}{R_w}) T_{out} + R (\frac{1}{R_n} + \frac{\zeta_D}{R_D}) T_n$

**Test4 - check the performance of Toffice-wall and Theater sensors**

ok (Toffice\_wall\_sensor)  $\rightarrow$  Toffice= $\tilde{T}$ office-wall  
ok (Theater\_sensor)  $\rightarrow$  Toffice= $\tilde{T}$ heater

**Test5 - check the performance of door-contact sensor, window-contact sensor, Theater sensor and the validity of the model (ok(room))**

ok (Theater\_sensor)  $\rightarrow$  Toffice= $\tilde{T}$ heater  
ok (door\_contact\_sensor)  $\rightarrow$   $\zeta_D = \tilde{\zeta}_D$   
ok (window\_contact\_sensor)  $\rightarrow$   $\zeta_W = \tilde{\zeta}_W$   
ok(room)  $\rightarrow \frac{d\tau}{dt} = \frac{R-R_i}{R_i^2 C_i} \tau + \frac{R}{R_i C_i} \phi_{in} + \frac{R}{R_i C_i} (\frac{1}{R_{out}} + \frac{\zeta_w}{R_w}) T_{out} + \frac{R}{R_i C_i} (\frac{1}{R_n} + \frac{\zeta_D}{R_D}) T_n$

ok(room)  $\rightarrow T_{in} = \frac{R}{R_i} \tau + R_i \phi_{in} + R (\frac{1}{R_{out}} + \frac{\zeta_w}{R_w}) T_{out} + R (\frac{1}{R_n} + \frac{\zeta_D}{R_D}) T_n$

**Test6 - check the performance of door-contact sensor, window-contact sensor, Toffice-wall sensor and the validity of the model (ok(room))**

ok (Toffice\_wall\_sensor)  $\rightarrow$  Toffice= $\tilde{T}$ office-wall  
ok (door\_contact\_sensor)  $\rightarrow$   $\zeta_D = \tilde{\zeta}_D$   
ok (window\_contact\_sensor)  $\rightarrow$   $\zeta_W = \tilde{\zeta}_W$   
ok(room)  $\rightarrow \frac{d\tau}{dt} = \frac{R-R_i}{R_i^2 C_i} \tau + \frac{R}{R_i C_i} \phi_{in} + \frac{R}{R_i C_i} (\frac{1}{R_{out}} + \frac{\zeta_w}{R_w}) T_{out} + \frac{R}{R_i C_i} (\frac{1}{R_n} + \frac{\zeta_D}{R_D}) T_n$   
ok(room)  $\rightarrow T_{in} = \frac{R}{R_i} \tau + R_i \phi_{in} + R (\frac{1}{R_{out}} + \frac{\zeta_w}{R_w}) T_{out} + R (\frac{1}{R_n} + \frac{\zeta_D}{R_D}) T_n$

Basing on the elementary models presented in section 3, 6 tests summarized by the following signature table have been deduced.

TABLE II: Signature Table

	Toffice_wall sensor	Toffice_reference sensor	Theater sensor	ROOM -SYSTEM
Test1	0	1	1	0
Test2	1	1	0	0
Test3	0	1	0	1
Test4	1	0	1	0
Test5	0	0	1	1
Test6	1	0	0	1

Note that ROOM-SYSTEM is a macro-item which combines the non discriminable items office-door-sensor, window-door-sensor and room. It is used to reduce the number of diagnoses.

### V. EXPERIMENTAL VALIDATION

#### A. Simulation scenarios

This section demonstrates the experimental validation of the proposed diagnosis method. Tests had been performed at the entire office including all sensors. In order to make an explicit and concise explanation, the following faulty scenarios have been considered:

- scenario 1: Toffice-reference sensor is subject to bias from  $t=2000$  until the end of simulation.
- scenario 2: Theater sensor gives null values from  $t=2000$  until the end of simulation.
- scenario 3: Door contact sensor, window contact sensor give random values from  $t=2000$  until the end of simulation.

The following figures represent the results of simulation for second scenario.

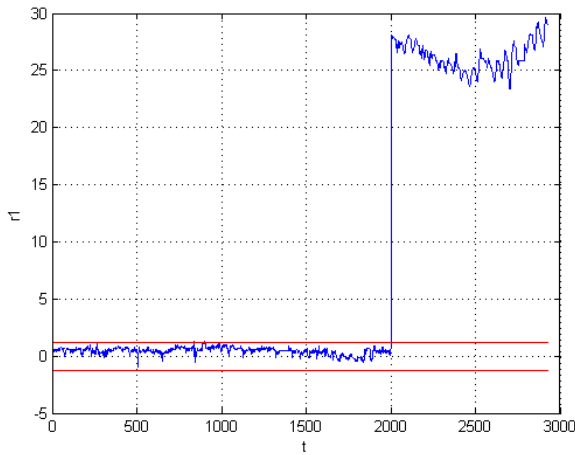


Fig. 2: Residual generation for test 1

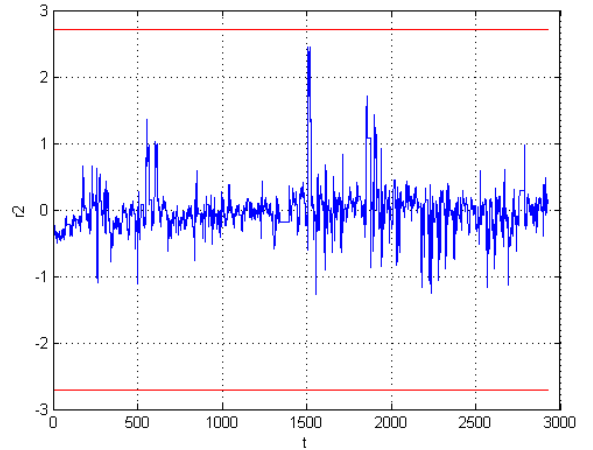


Fig. 3: Residual generation for test 2

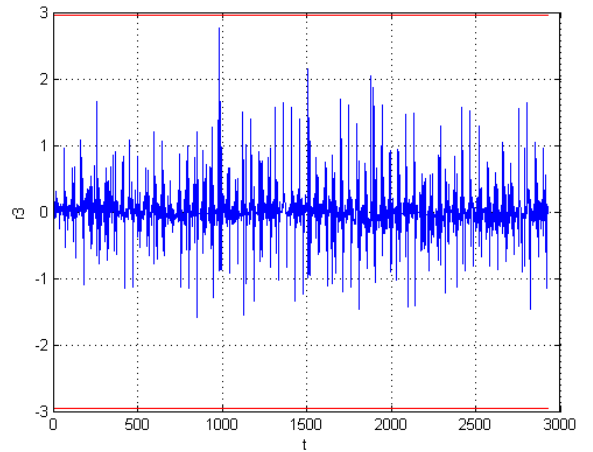


Fig. 4: Residual generation for test 3

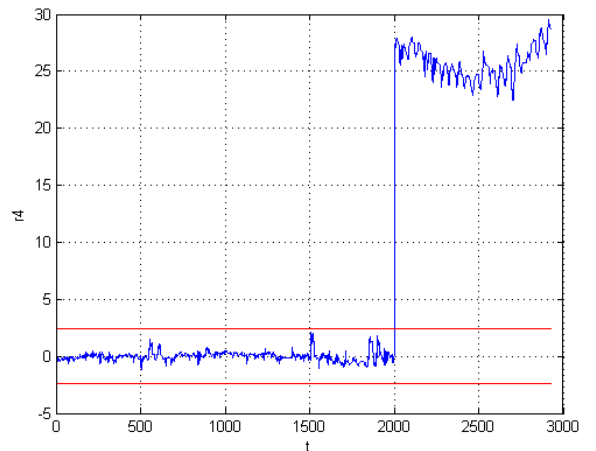


Fig. 5: Residual generation for test 4

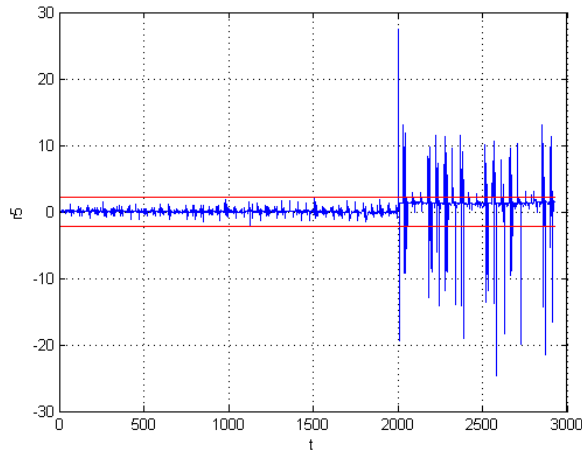


Fig. 6: Residual generation for test 5

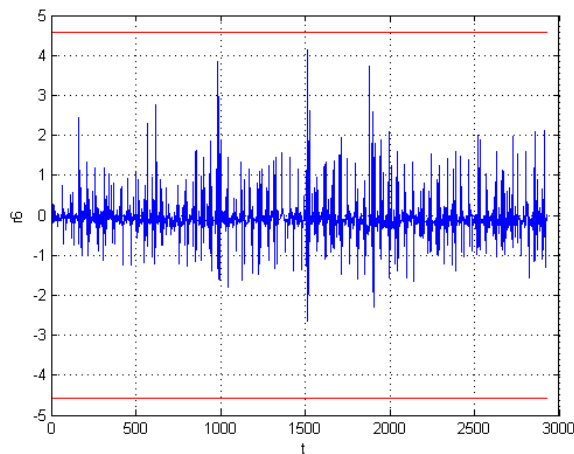


Fig. 7: Residual generation for test 6

#### Interpretation:

In the second scenario, we suppose that Theater sensor is faulty. The residual generation for this scenario is described in Fig. 2, Fig. 3, Fig. 4, Fig. 5, Fig. 6 and Fig. 7.

In fact, before the appearance of fault, the signature is  $(0, 0, 0, 0, 0, 0)$ . When the fault appears at  $t=2000$ , we notice that residues deviate from zero and the signature become  $(1, 0, 0, 1, 1, 0)$ . If we compare this new signature with that at TABLE 2, we conclude that Theater sensor is faulty.

Note that only the scenario 2 is presented. Similar simulation results concerning the other scenarios are omitted for reason of space.

#### B. Diagnosis analysis and fault isolation

A test is defined by the following entities:

- the components that were involved in the test.
- the symptom that was observed when comparing results with expectations.

In practice, tests are performed out of the application to see how the system responds to given situations or inputs. A symptom is what the user observes when comparing the behavior of the system during a test with the results that were expected. The following values for symptoms can be obtained:

- Negative: if the system does not behave as expected, the test will be considered as failed and the symptom will be negative.
- Positive: if the system behavior is consistent with the reaction that was expected, the test is considered successful and the symptom will be positive.

Diagnoses with all kind of possible faults are found thanks to:

- Hitting Tree Set algorithm
- Hamming distance between diagnosis and effective signature
- Fault probability

The following table (Table 3) summarizes the BRIDGE possible diagnosis and actual fault for each scenario.

TABLE III: Diagnosis result and fault explanation

Scenarios	BRIDGE possible diagnosis	Actual fault	Conclusion
Scenario 1	Toffice-reference (66.66%) Theater (66.66%)	Toffice-reference	Accurate diagnosis
Scenario 2	Theater (100%) ROOM-SYSTEM, Toffice-wall, Toffice-reference (50%)	Theater	Accurate diagnosis
Scenario 3	ROOM-SYSTEM Toffice-wall, Theater, Toffice-reference (50%)	door-contact, window contact	Not accurate diagnoses

## VI. CONCLUSION

This paper presents a methodology for diagnosis of sensor grids which ensure the localization of sensor fault. Sensor faults are diagnosed using detection tests and diagnosis from first principle.

The simulation results prove that, if the tests are coherent with reality, the proposed approach leads to an accurate diagnoses. However, it is not always possible to construct tests that exactly coincide with reality. That's why, the proposed approach leads to an inaccurate diagnoses in some cases. Thus, we need additional sensors. Forming another tests can be done to prove diagnosis accuracy.

Future work will revolve around developing a diagnosis analysis system dedicated to sensor grids in the building in a multi-zone context.

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