Embedded Controllers for Increasing HVAC Energy Efficiency by Automated Fault Diagnostics

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Outline

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- Honeywell Building Solutions (HBS)
- JACE controller (embedded system)
- HVAC diagnostics
  - Air Handling Unit (AHU)
- AFDD algorithm
  - Data Cleansing
  - Mode Detection
  - System Observation
  - Fault Isolation
- Examples

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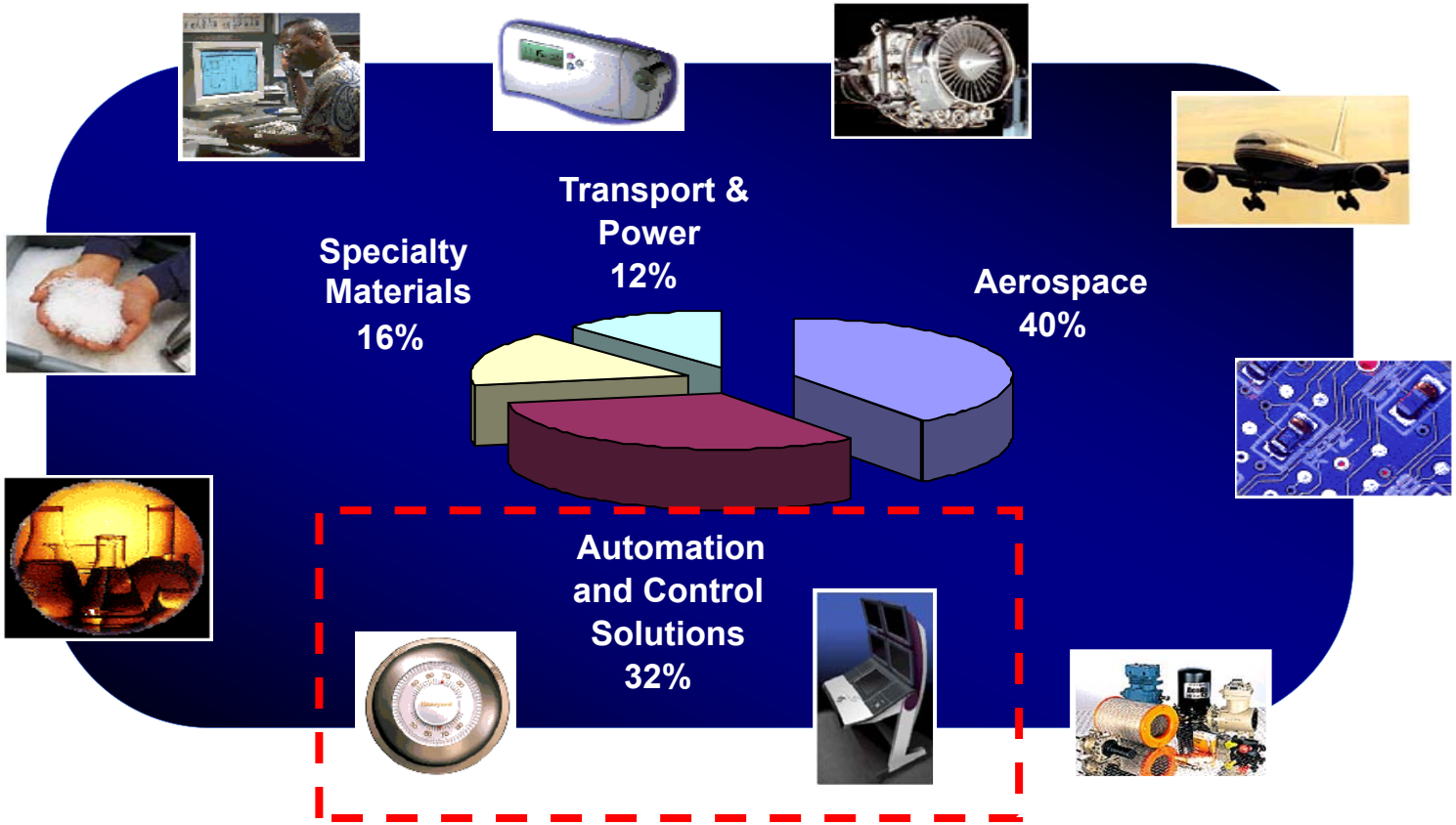
Specialty Materials 16%
Transport & Power 12%
Aerospace 40%
Automation and Control Solutions 32%

Automation & Control Solutions (ACS)

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Profile

More than 50,000 employees

Honeywell Process Solutions	Honeywell Building Solutions	Honeywell Sensing & Control	Honeywell E & C Control	Honeywell Security	Honeywell Life Safety
Process Controls	Buildings	Speed and Position Sensors	Thermostats	Motion / Human Presence Sensors	Fire/Smoke Sensors
Distributed Control	Instant Alert	Accelerometers	Building Automation	CCTV/ DVR User Interfaces	System Panels
EXPERION PKS Process Knowledge System		Pressure Sensors	Water Control	Control Systems	Home Medical Care
			Gas Valves		

Embedded System (JACE)

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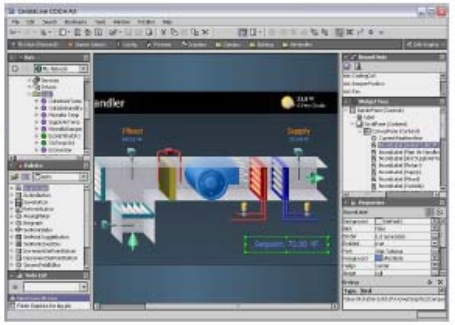
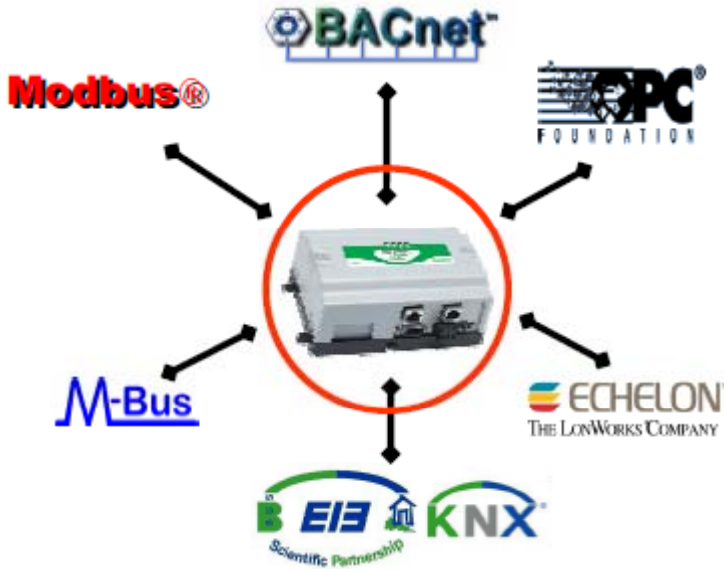
- **JACE = JAVA® Application Control Engine**
- **Integration Controller**
  - **Integrator**
    - Integration of communication protocols (LON, BACnet, Modbus etc.)
    - Graphical interface & Built-in web server
    - Data processing capability (e.g. AFDD)
  - **Controller**
    - Freely programmable DDC controller

JACE



Graphical interface (e.g. AHU schematics)

Multiple protocols



JACE: Integration Controller

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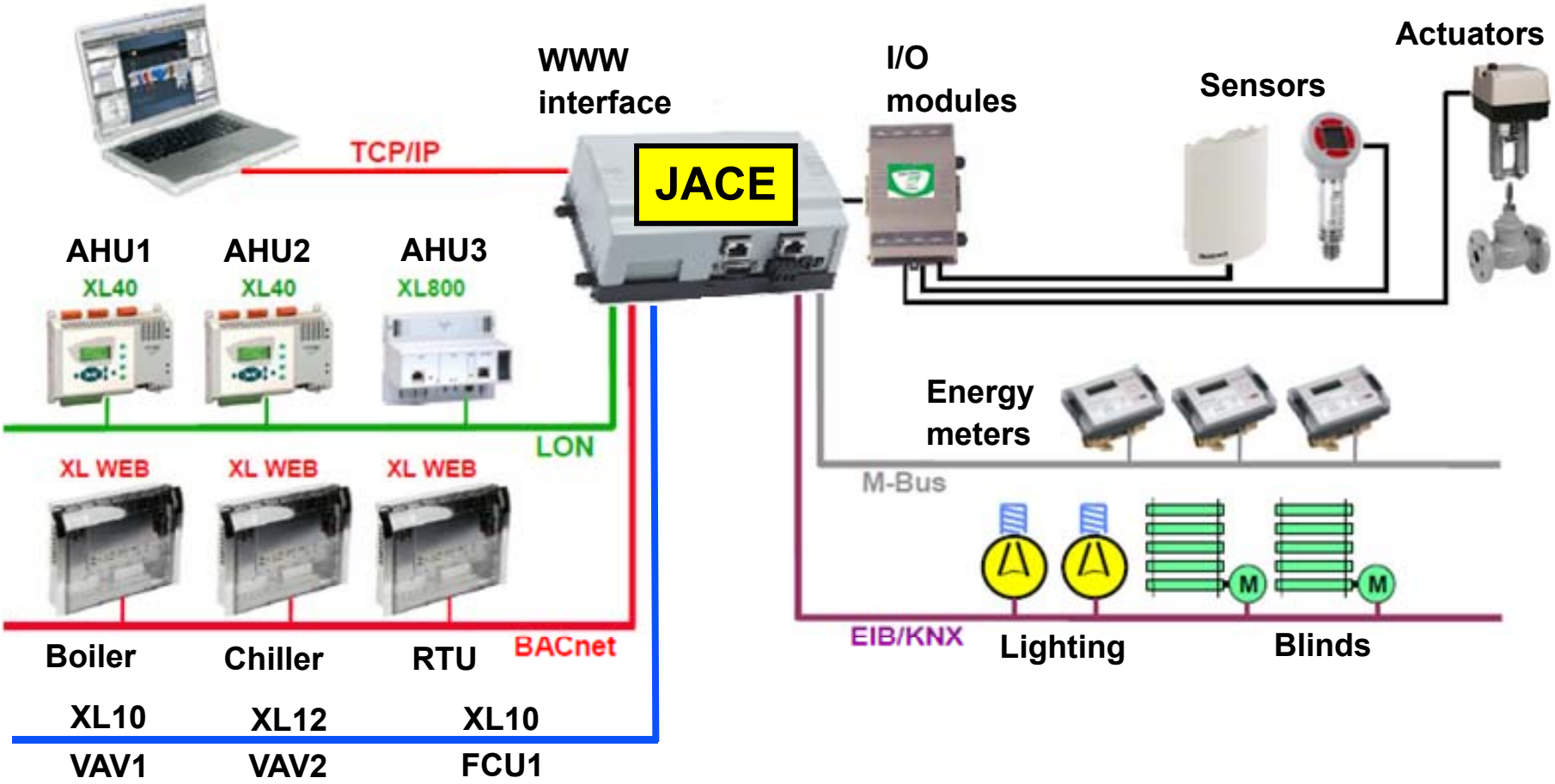
- **Integration of various building subsystems**
  - **HVAC; Lighting; Metering**
- **Multiple protocols to communicate with:**
  - **Plant controllers** (Boiler, Chiller, Air handlers)
  - **Room controllers** (VAV terminals, Fan coil units)



Next Generation of JACE controllers

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- **HVAC Diagnostics in JACE**
  - **Automated fault detection**
    - HVAC equipment - Boilers, Chillers, AHUs, VAV terminal units, Fan coils
    - Auxiliary devices - Pumps, Fans, Valves, etc.
  - **Present AFDD results using:**
    - Online diagnostic screens - GUI
    - Diagnostic reports - Charts, tables, recommendations

- **Challenge = Address practical aspects:**
  - **Different levels of instrumentation**
    (Scenarios according to available sensors)
  - **Contextual information from BIM**
    (e.g. Automatically modify diagnostic rules based on given HVAC configuration)
  - **Monetization**
    (Convert degraded equipment performance to financial loss)

HVAC Equipment

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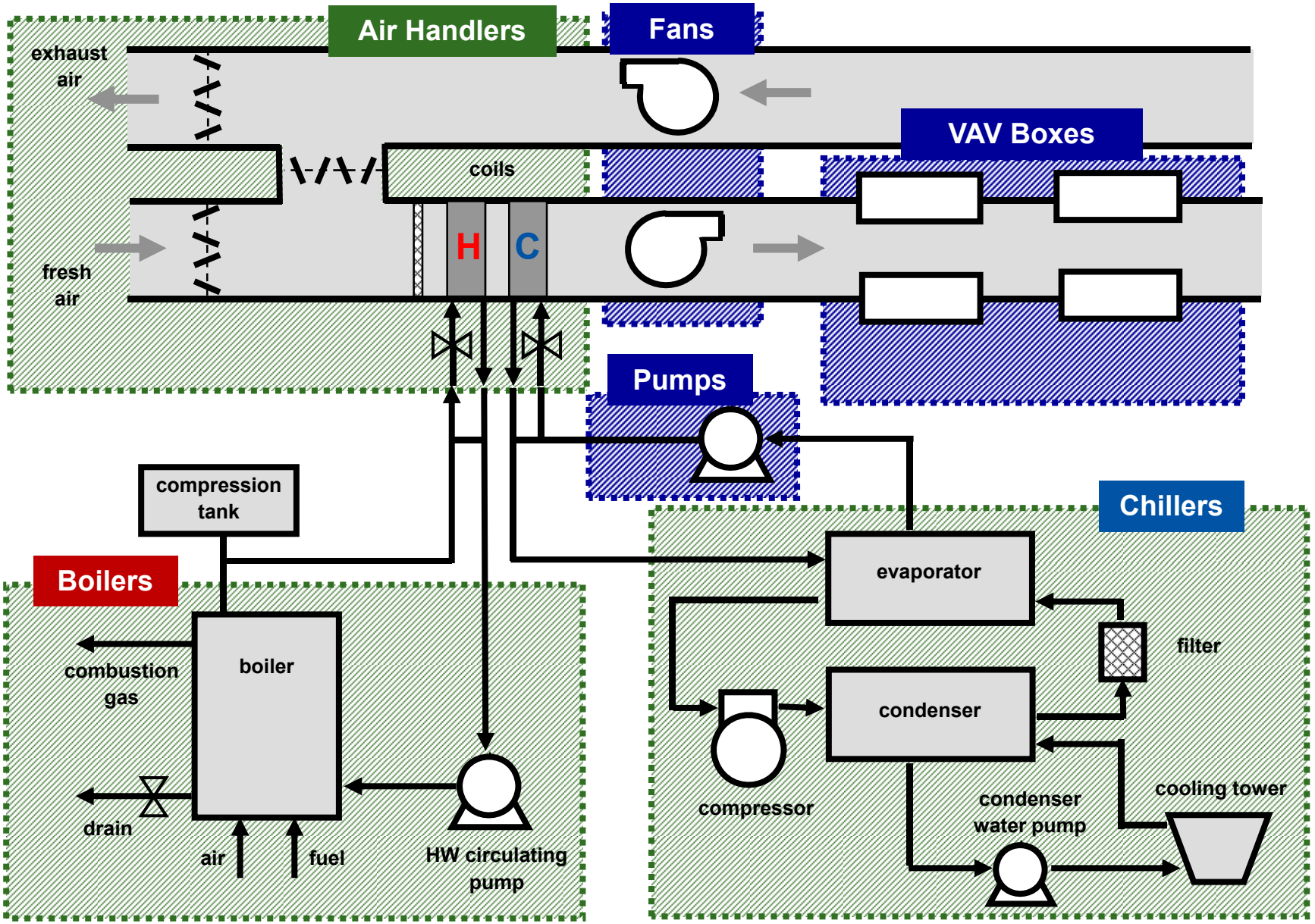

Air Handling Unit (AHU)

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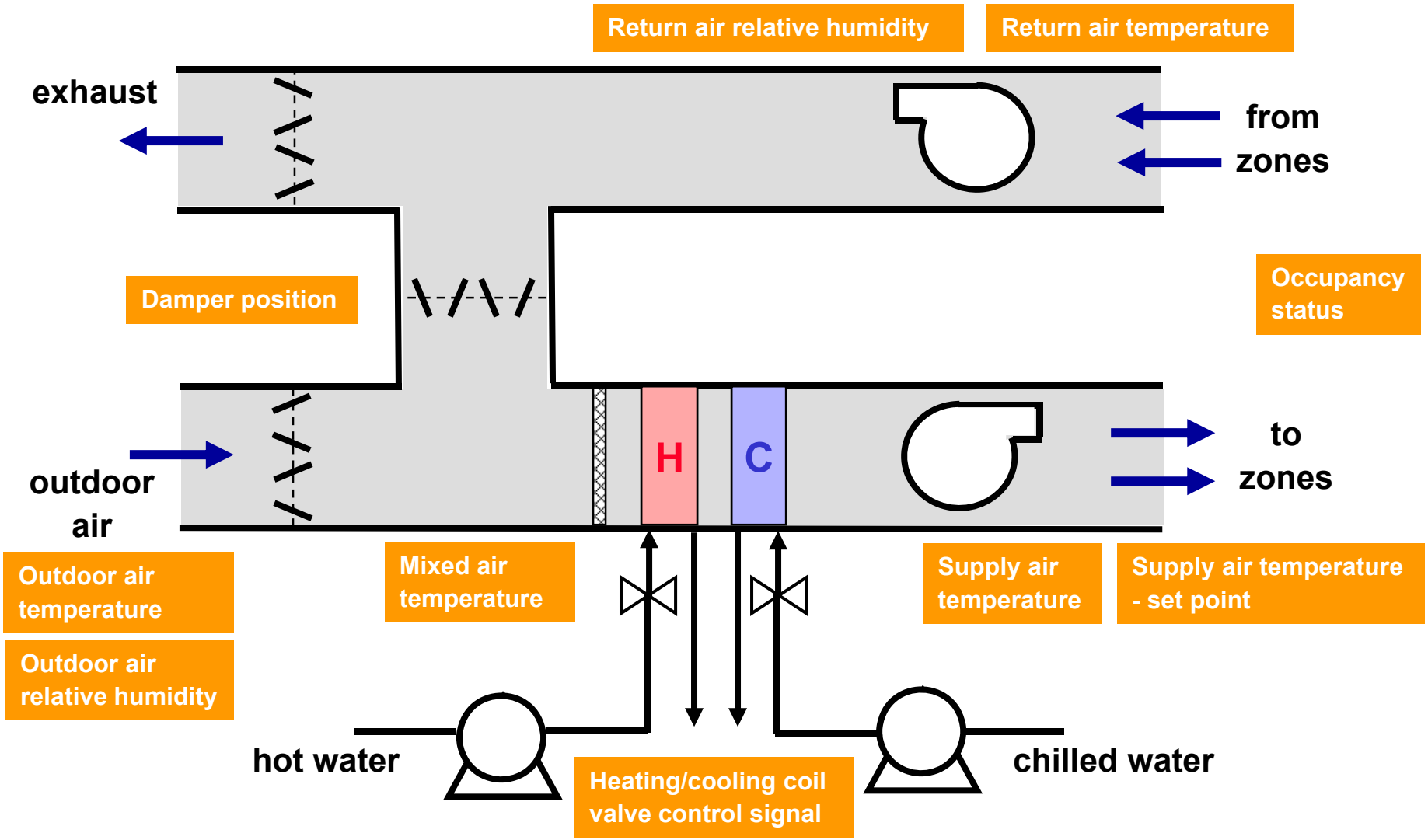

Types of AHU Faults

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- **Hardware Faults**
  - **Abrupt Faults**
    - Damper faults - stuck damper
    - Valve faults - stuck or leaking valve (of heating/cooling coil)
    - Heating/cooling failure
    - Sensor faults - frozen sensor, noisy data, missing values, outliers
  - **Performance Degradation**
    - Air filter clogging
    - Heating/cooling coil scaling
    - Sensor drift/bias
- **Control System Faults**
  - **Control Loop Performance**
    - Missed setpoint (permanent offset)
    - Oscillating control signal - e.g. due to wrong PID parameters
    - Excessive overshoot
    - Long settling time
  - **Control Strategy**
    - Simultaneous heating & cooling
    - Using mechanical cooling instead of ventilation (free cooling)
    - Wrong sequencing (Late/early start & stop)

AFDD implementation in JACE

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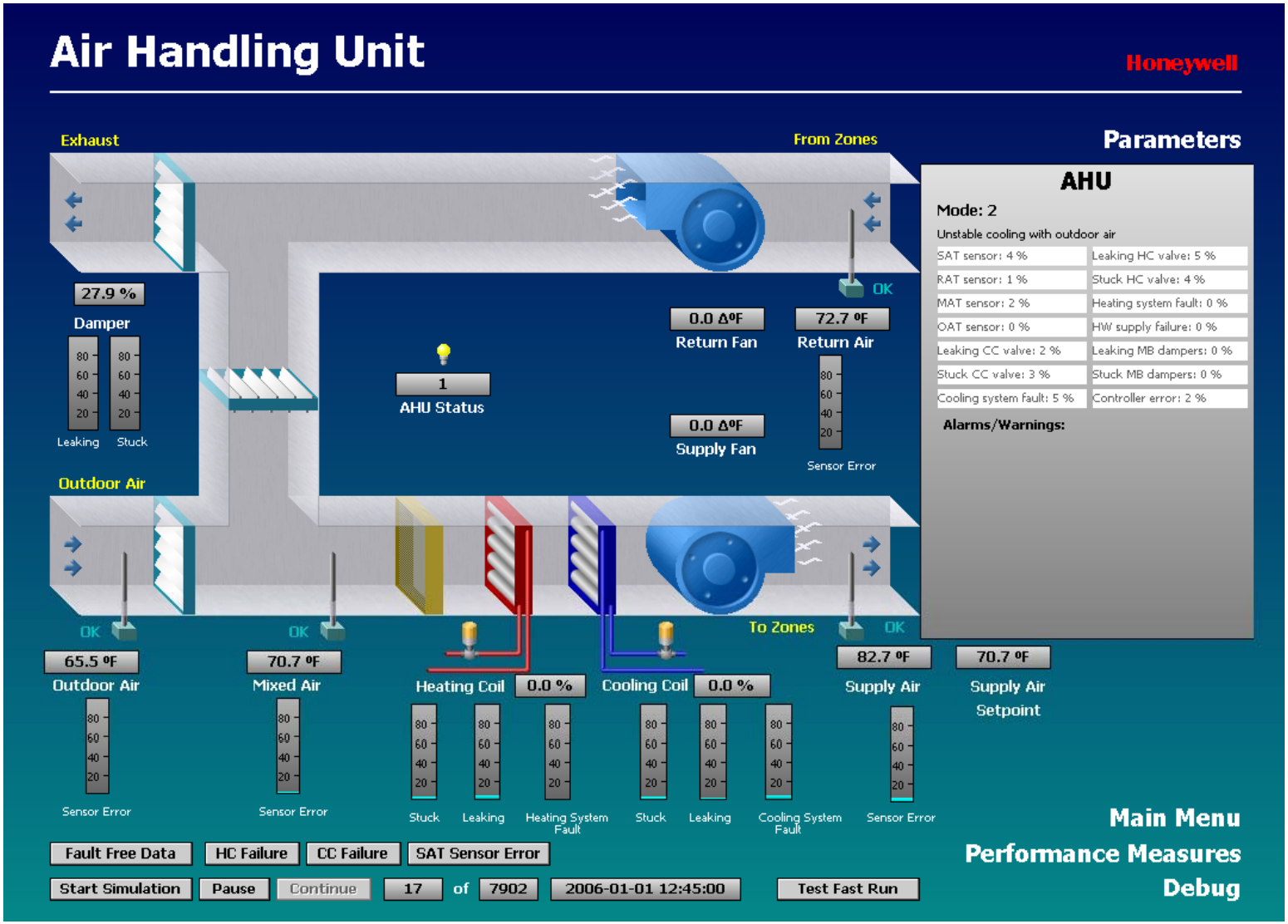

Module 1: Data Cleansing

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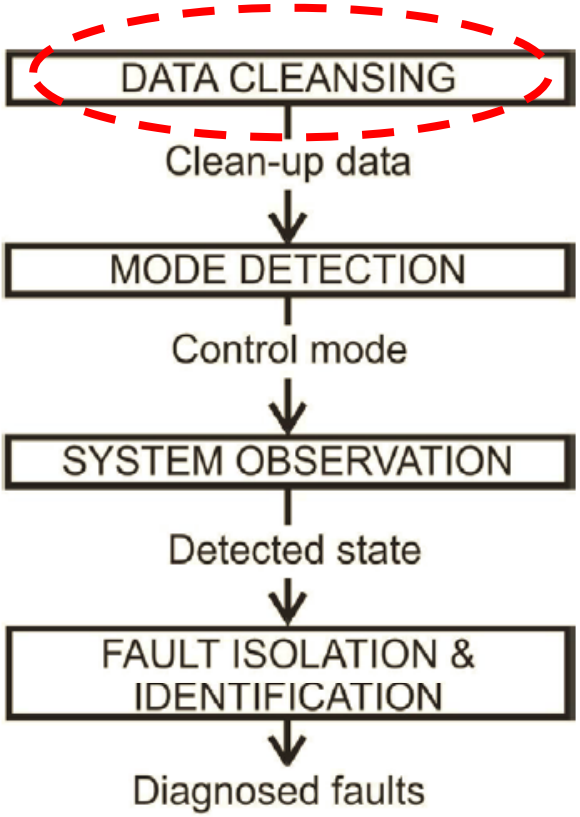

Data Type	Data Error	Method to detect
Control signals for: • heating coil valve • cooling coil valve • mixing box damper • supply fan drive	Oscillations	✓
	Outliers	✓
Sensor signals • temperature • static pressure • mass flow • humidity • etc.	Outliers	✓
	Frozen Sensor	being developed
	Missing Data	not addressed
	Sensor Bias	✗
	Sensor Drift	✗

Control Signals: Oscillations & Outliers

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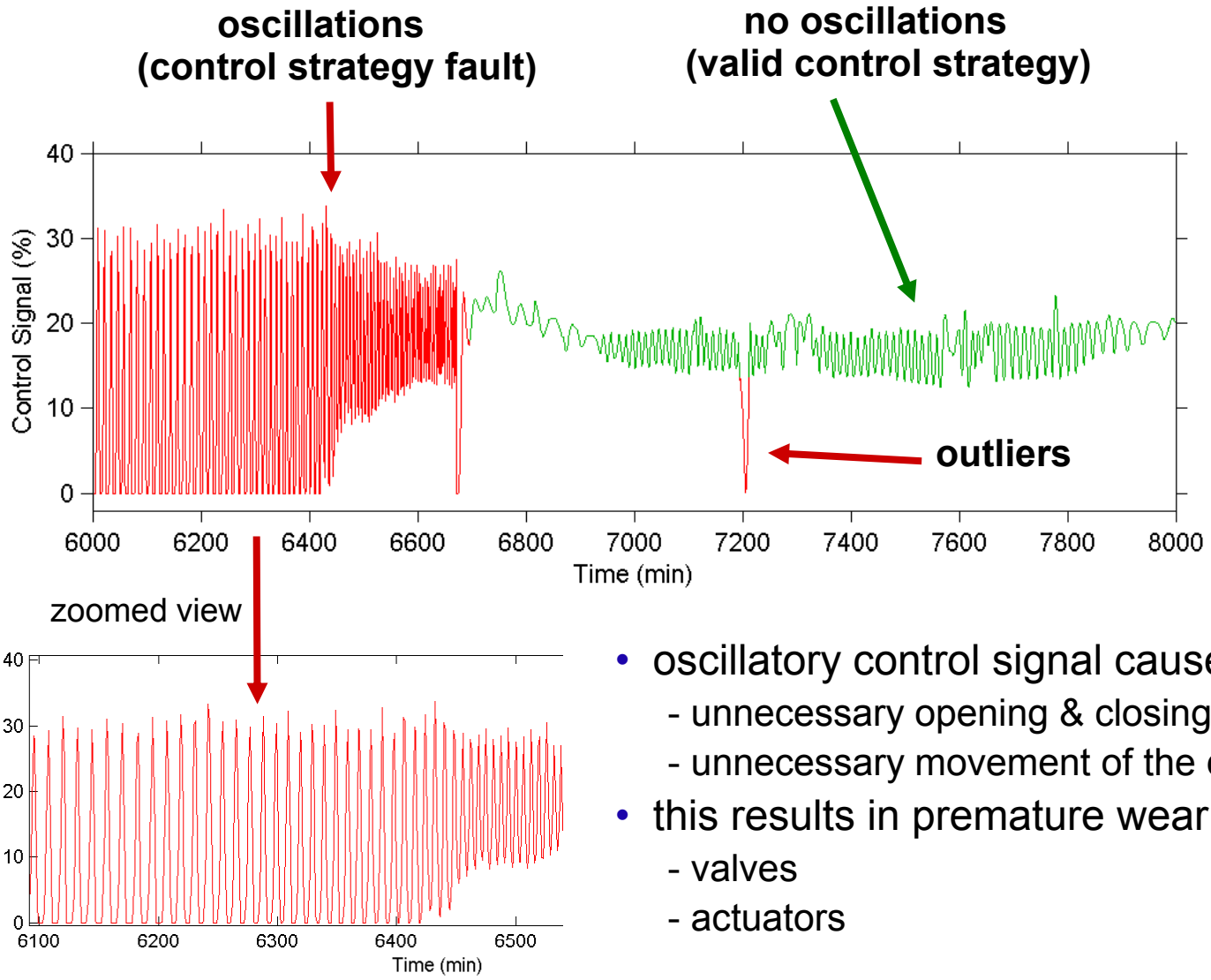

- oscillatory control signal causes:
  - unnecessary opening & closing of the valves
  - unnecessary movement of the dampers
- this results in premature wear and failure of:
  - valves
  - actuators

Method 1: Oscillation Detector

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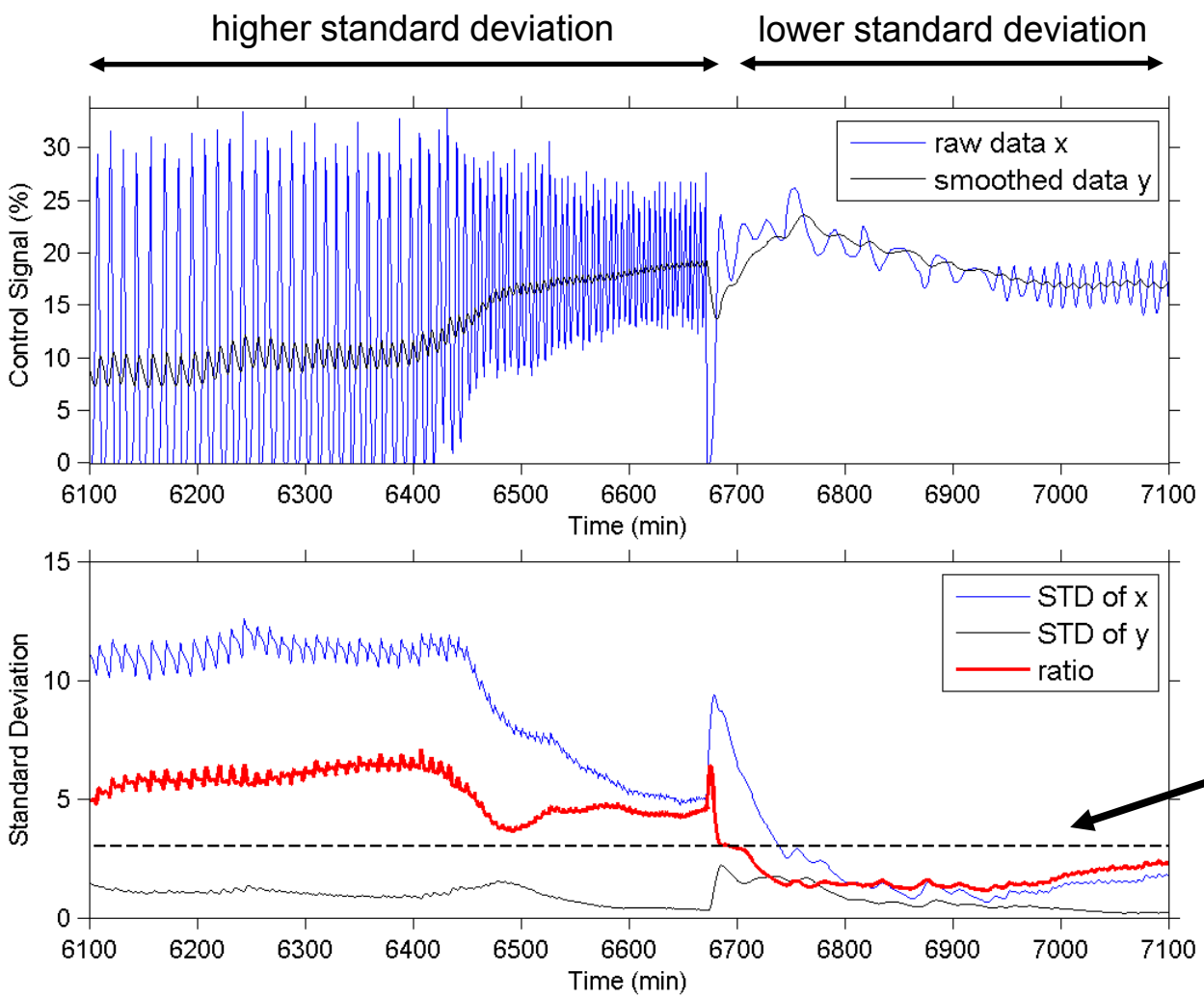

raw data

$$\text{STD Ratio} = \frac{1+\text{STD}(x[k])}{1+\text{STD}(y[k])}$$

smoothed data
(**low-pass** filtered)

threshold = 3

Method 2: Outlier Detector

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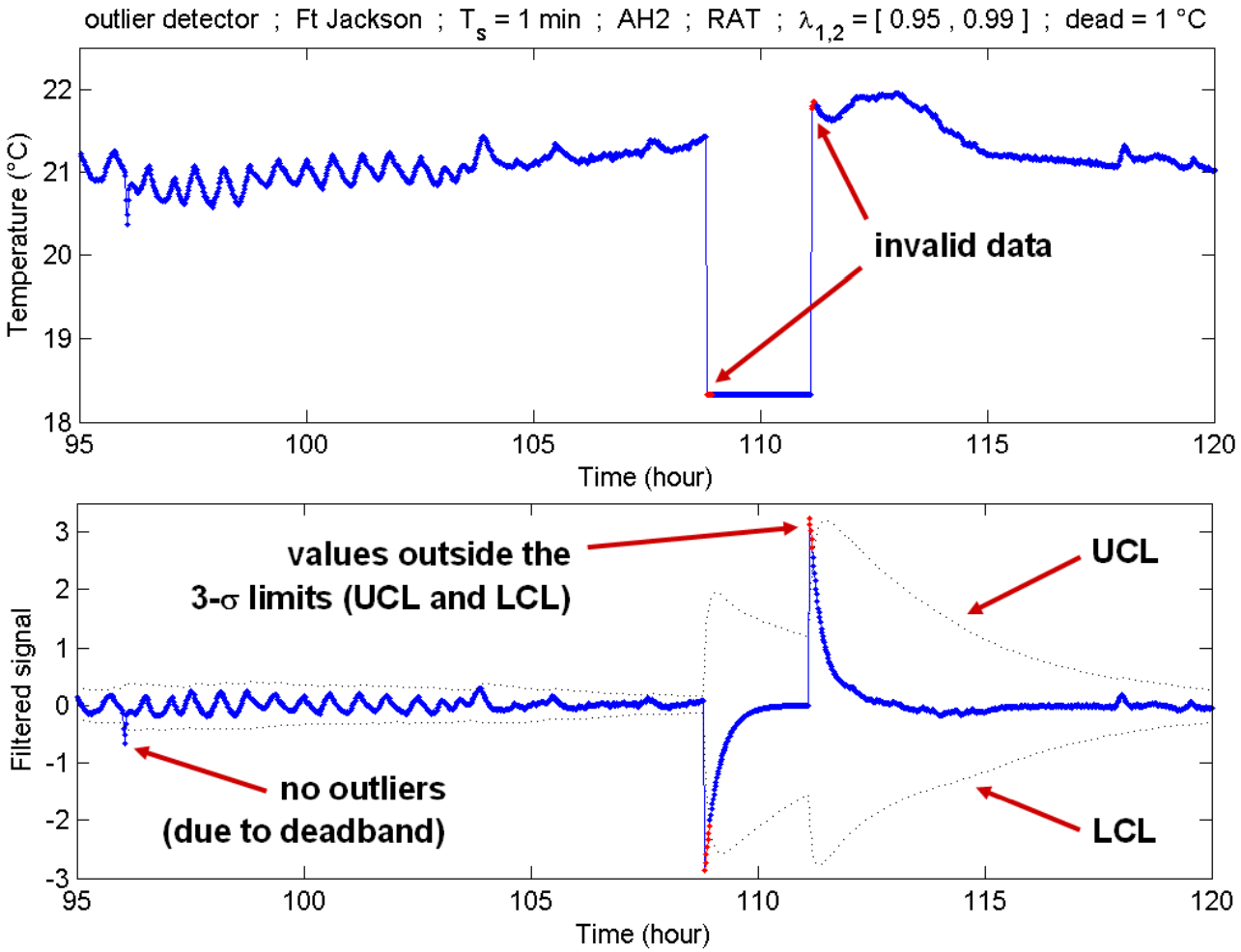

low-pass filtered

$$z[k] = x[k] - y[k]$$

high-pass filtered

three-sigma limits:

$$UCL = \mu_z[k] + 3\sigma_z[k]$$
$$LCL = \mu_z[k] - 3\sigma_z[k]$$

Module 2: Mode Detection

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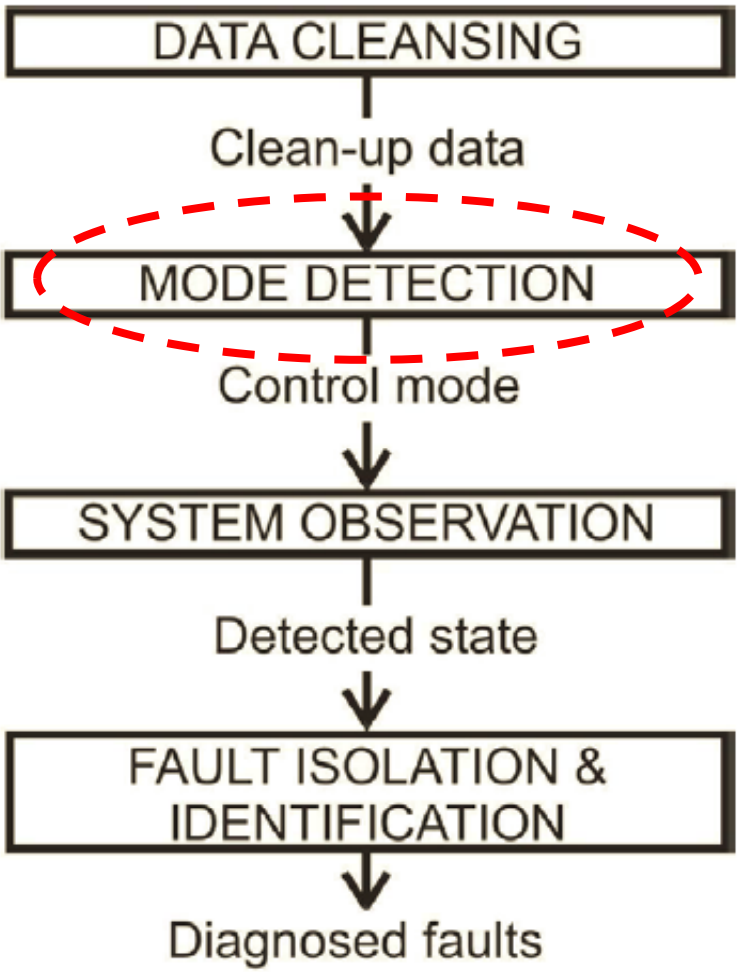

AHU Operation Mode

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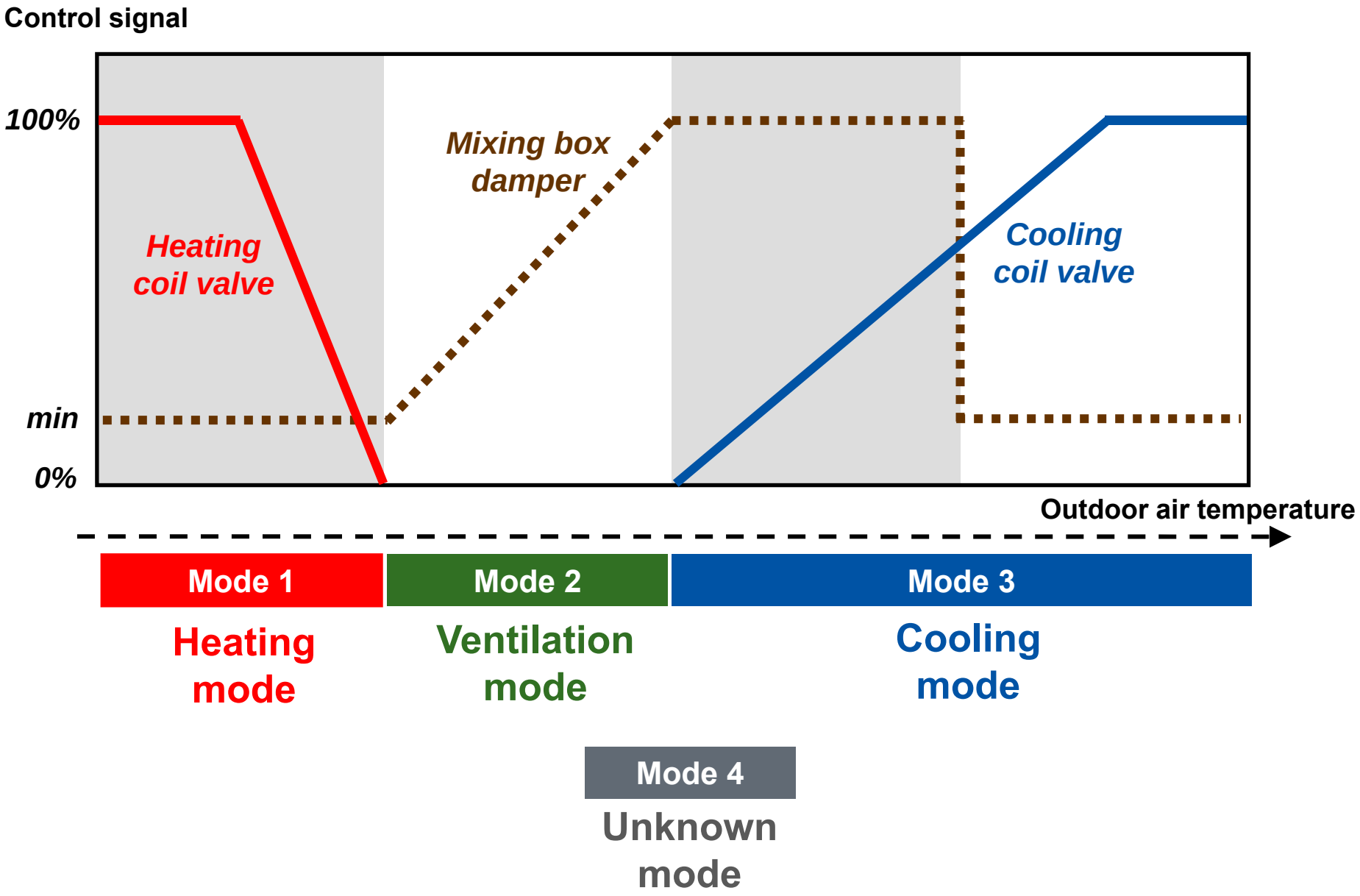

AHU Operation Mode

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- **AHU mode**
  - **Determined by controller using temperatures** (or enthalpies)
  - **AFDD algorithm detects AHU mode using control signals only**
- **Finding stabilized mode:**
  - **Heating mode:** c_h **> 30 min**
  - **Cooling mode:** c_c **> 30 min**
  - **Ventilation mode:** c_v **> 30 min**

Sampling period (e.g. 5 min)

Threshold on control signals

Counter for Heating mode

$$c_h(t) = \begin{cases} c_h(t-1) + T_s & \text{if } U_{HC}(t_i) > 2\% \text{ and } U_{CC}(t_i) < 2\% \\ 0 & \text{otherwise} \end{cases}$$

Counter for Cooling mode

$$c_c(t) = \begin{cases} c_c(t-1) + T_s & \text{if } U_{HC}(t_i) < 2\% \text{ and } U_{CC}(t_i) > 2\% \\ 0 & \text{otherwise} \end{cases}$$

Counter for Ventilation mode

$$c_v(t) = \begin{cases} c_v(t-1) + T_s & \text{if } U_{HC}(t_i) < 2\% \text{ and } U_{CC}(t_i) < 2\% \\ 0 & \text{otherwise} \end{cases}$$

Module 3: System Observation

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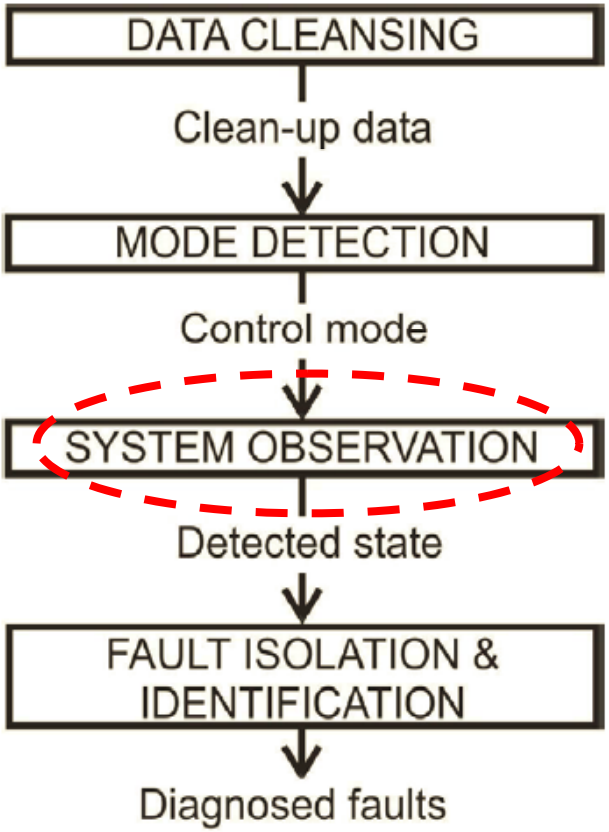

Vector of Measurements:

$$\mu = [T_{MA}, T_{SA}, T_{SAS}, U_{HC}, U_{CC}]$$

Observation o2

- **Function of supply air temp & setpoint**
- **Three possible values: 1, 0, -1**

$$o_2(\mu) = \begin{cases} 1 \text{ if } T_{SA} > T_{SAS} + \varepsilon_T & \text{above setpoint} \\ 0 \text{ if } T_{SA} = T_{SAS} \pm \varepsilon_T & \text{setpoint is met} \\ -1 \text{ if } T_{SA} < T_{SAS} + \varepsilon_T & \text{below setpoint} \end{cases}$$

Observed State

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- Mapping between observations & states
  - Each state defined by particular combination of o1, o2 & o3
- 45 possible states of the AHU (states are mutually exclusive)
  - States are classified as normal and abnormal

Heating Mode

	Observations			Behavior
	o1	o2	o3	
State 1	1	0	0	normal
State 2	1	0	1	normal
State 3	1	-1	0	abnormal
State 4	1	-1	1	abnormal
State 5	1	1	0	abnormal
State 6	1	1	1	abnormal
State 7	-1	0	0	abnormal
State 8	-1	0	1	abnormal
State 9	-1	-1	0	abnormal
State 10	-1	-1	1	abnormal
State 11	-1	1	0	abnormal
State 12	-1	1	1	abnormal
State 13	0	0	0	abnormal
State 14	0	0	1	abnormal
State 15	0	-1	0	abnormal
State 16	0	-1	1	abnormal
State 17	0	1	0	abnormal
State 18	0	1	1	abnormal

Cooling Mode

	Observations			Behavior
	o1	o2	o3	
State 1	1	0	0	abnormal
State 2	1	0	1	abnormal
State 3	1	-1	0	abnormal
State 4	1	-1	1	abnormal
State 5	1	1	0	abnormal
State 6	1	1	1	abnormal
State 7	-1	0	0	normal
State 8	-1	0	1	normal
State 9	-1	-1	0	abnormal
State 10	-1	-1	1	abnormal
State 11	-1	1	0	abnormal
State 12	-1	1	1	abnormal
State 13	0	0	0	abnormal
State 14	0	0	1	abnormal
State 15	0	-1	0	abnormal
State 16	0	-1	1	abnormal
State 17	0	1	0	abnormal
State 18	0	1	1	abnormal

Ventilation Mode

	Observations			Behavior
	o1	o2	o3	
State 1	1	0	0	abnormal
State 2	1	-1	0	abnormal
State 3	1	1	0	abnormal
State 4	-1	0	0	abnormal
State 5	-1	-1	0	abnormal
State 6	-1	1	0	abnormal
State 7	0	0	0	normal
State 8	0	-1	0	abnormal
State 9	0	1	0	abnormal

Module 4: Fault Isolation & Identification

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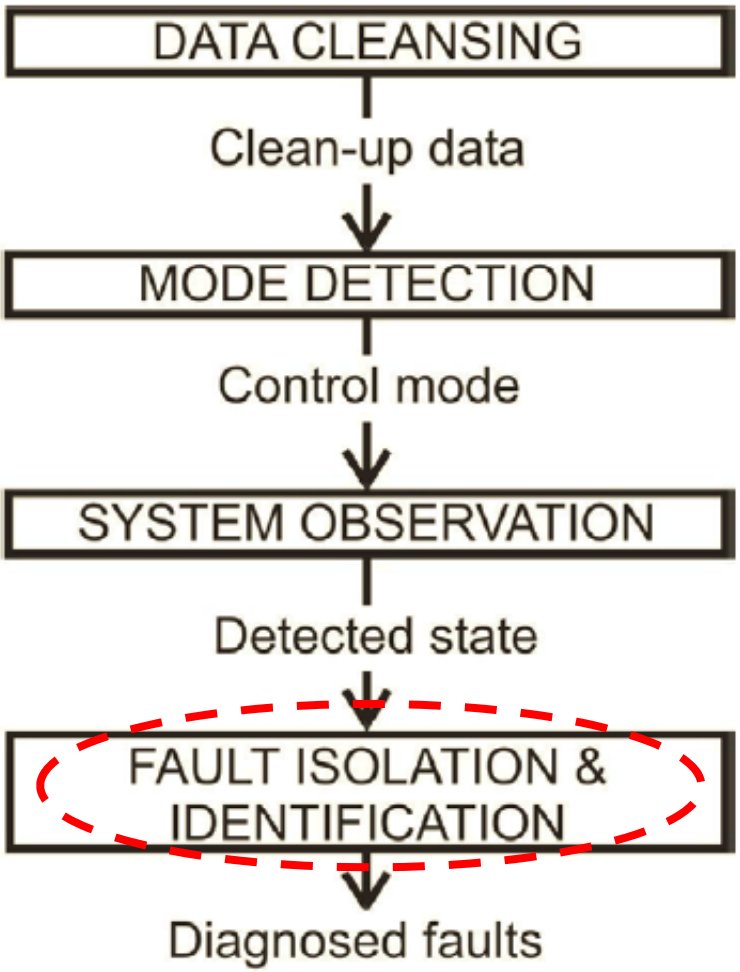

Mapping Table

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- **Mapping between abnormal states & faults**
  - Binary diagnostic matrix
  - Represents the expert knowledge

		Fault						
AHU Mode	Observed State	F1	F2	F3	F4	F5	F6	F7
Heating	s3, s5, s6	1	0	0	0	0	0	1
Heating	s4	1	1	0	1	0	0	1
Heating	s7, s8	1	0	0	0	0	0	1
Heating	s7, s10, s11, s12	1	0	0	0	0	0	0
Heating	s13, s14, s15, s17, s18	0	1	0	1	0	0	0
Heating	s16	1	1	0	1	0	0	0
Cooling	s1, s2	0	1	0	0	0	0	1
Cooling	s3, s4, s5, s6	0	1	0	0	0	0	0
Cooling	s9, s10, s11	0	1	0	0	0	0	1
Cooling	s12	0	1	1	0	0	0	1
Cooling	s13, s14, s15, s16, s17	1	0	1	0	0	0	0
Cooling	s18	1	1	1	0	0	0	0
Ventilation	s1	0	1	0	0	0	1	0
Ventilation	s3, o5	0	1	0	0	0	0	0
Ventilation	s7	1	0	0	0	1	0	0
Ventilation	s9, s11, s15, s17	1	0	0	0	0	0	0

1 = fault
0 = don't know

State s12 implies faults F2, F3 & F7 ←

State s1 implies faults F2 & F6 ←

Fault Aggregation

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- **Fault Relevance** is updated in time using CUSUM:

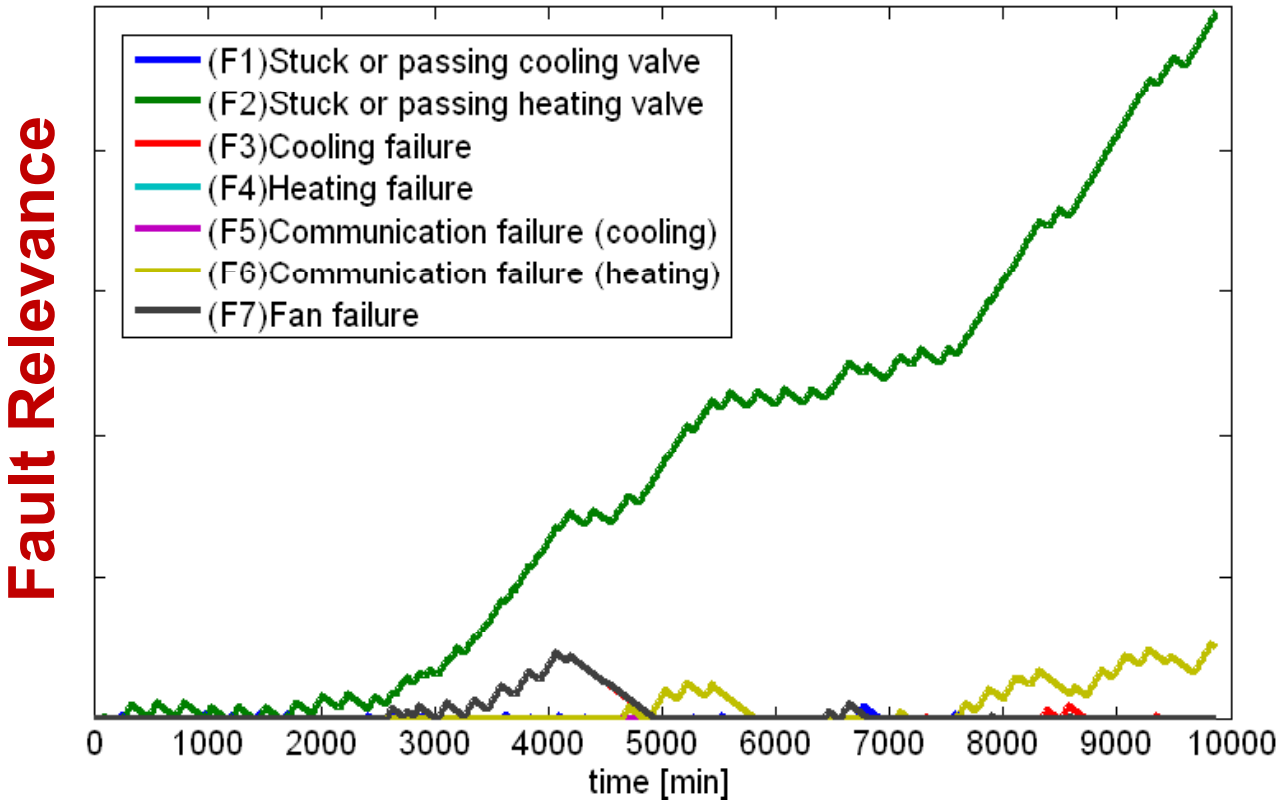
$$R_i(t) = \max\{\, 0,\ m(f_i, s_j) - k + R_i(t-1) \,\}$$

Current value

Mapping function output, 0 or 1

Forgetting factor, k=0.3

Previous value



Example 1: Stuck Heating Valve

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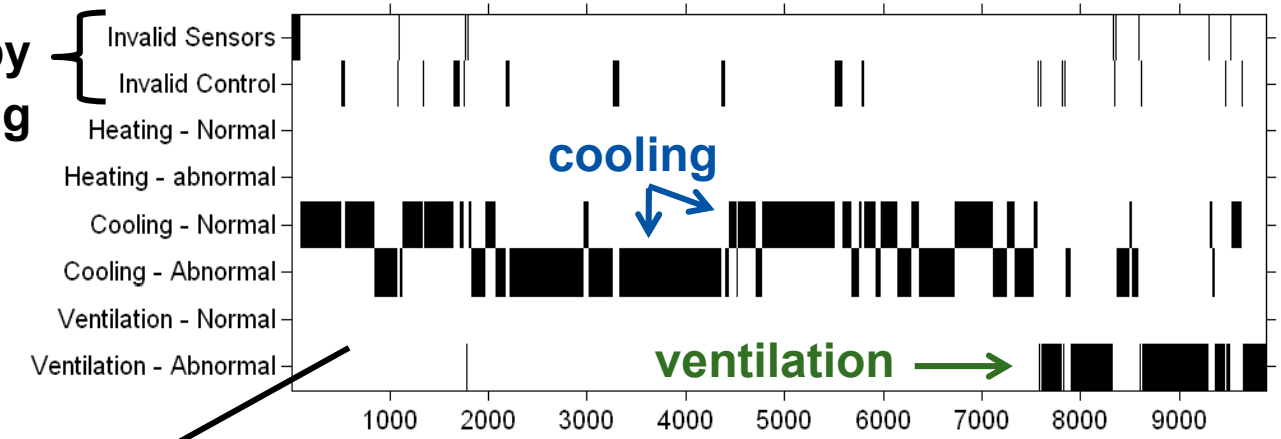
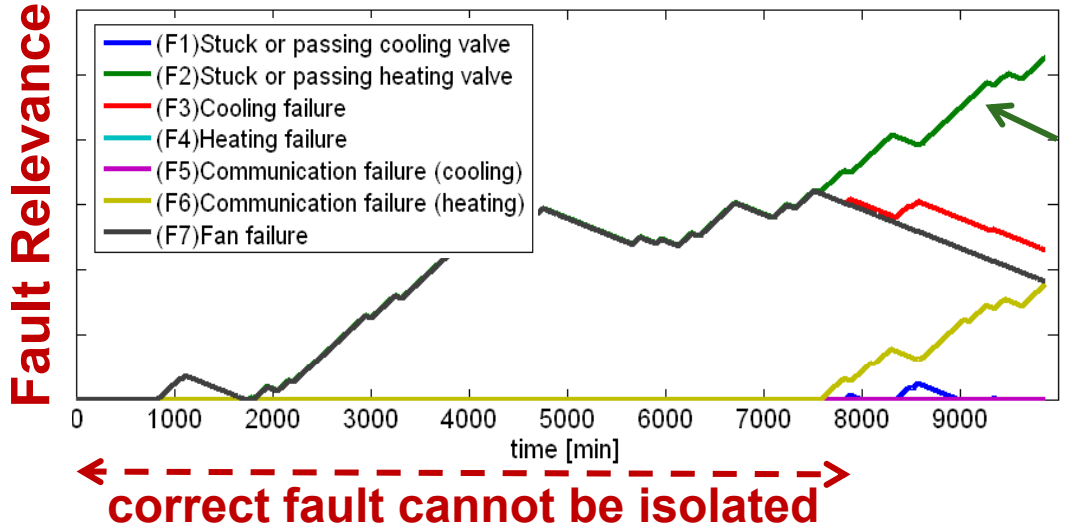
- **Air was heated despite $U_{HC} = 0$** (heating control signal)
- **Controller compensates by increasing U_{CC}** (cooling control signal)
- **Simultaneous heating & cooling ⇒ wasted energy ⇒ financial losses**

detected by data cleansing



only one AHU state at each time instant



correct fault cannot be isolated

Most likely fault is F2 (stuck heating valve)

(confirmed by building technician)

Example 2: Oscilating control signal

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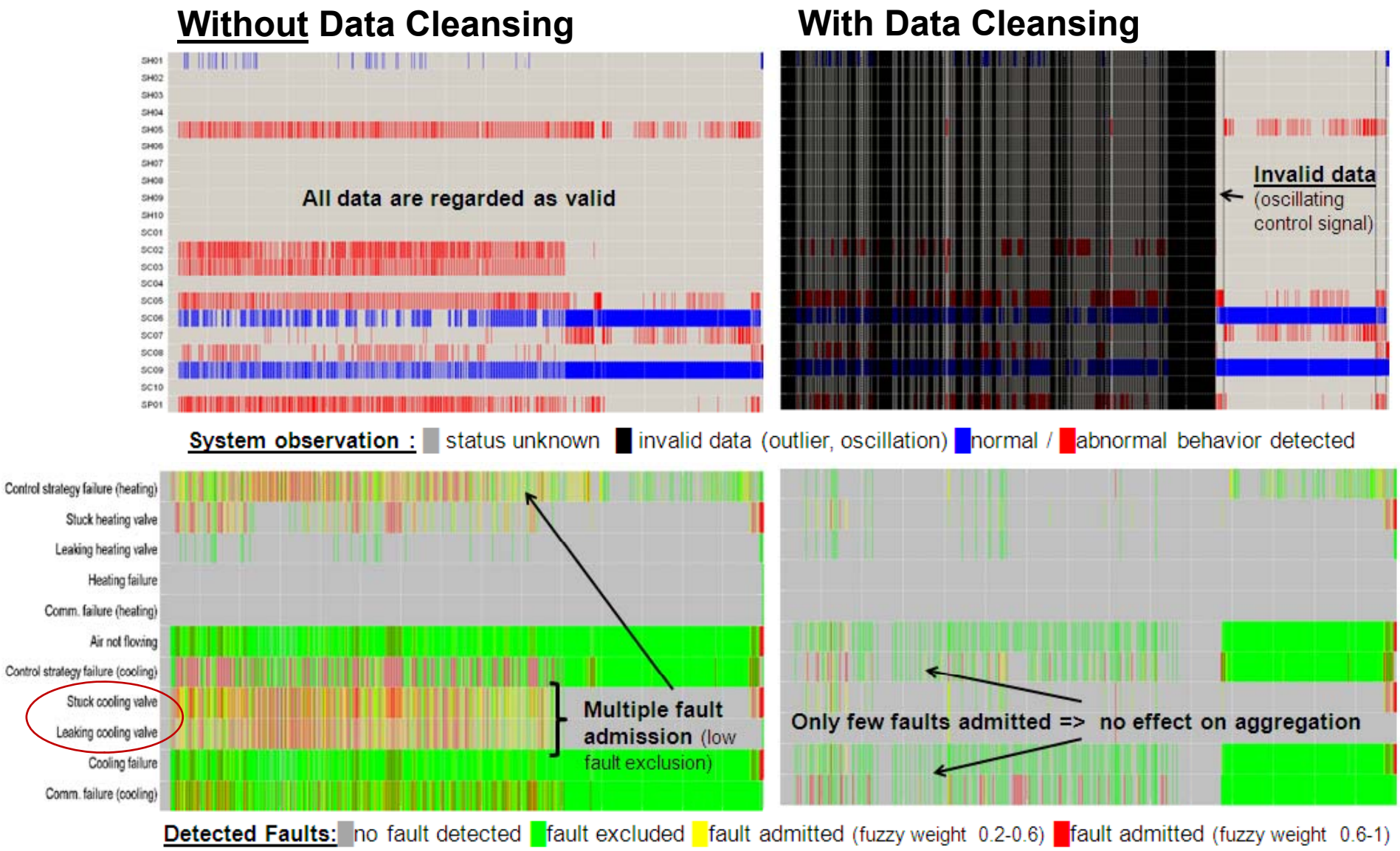

Data cleansing needed to avoid detection of non-existing faults

Summary

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- **AFDD algorithm for HVAC equipment**
  - **HVAC system = Major energy consumer in buildings**
  - **Reduce energy wasting by automated detection of HVAC faults**
    - Abrupt hardware faults; Performance degradation
  - **Performed by Honeywell JACE controller (embedded system)**
  - **Graphical visualization in JACE**
    - AHU scheme, Measured data, Observed state, Fault relevances
- **AHU diagnostics**
  - **Rule-based diagnostics** (based on APAR by Schein et al.)
  - **Data cleansing module**
    - Detect raw data errors (outliers, oscillations, etc.)
    - Protects the AFDD algorithm from wrong decision (hoax faults)
  - **Diagnostic mapping table**
    - Measurements → Observations → States → Faults
  - **Fault aggregation**
    - Fault relevance (of each fault) is updated in time