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Building system diagnostics through a network of smart local sensors

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***Abstract*— The study describes the design and implementation of automated fault detection and diagnostics (AFDD) for office building systems. This work is part of larger research focused on distributed digital collaboration framework used in Facility Management. The implementation fully exploits distributed computing to make it possible remote and smart monitoring of the building, anomaly detection and eventually fault diagnostics. A huge number of data are gathered locally by smart sensors that are integrated and interconnected by Internet of Things (IoT). Local intelligence allows both anomaly detection and fault diagnostics: identification of the cause of the fault and choice of the corrective action. IoT allows to transfer on the cloud processed information, on higher level of abstraction, in order to execute diagnostics of the entire building system. Distributed diagnostics requires the collection and harmonization of a huge number of feature data and the extraction of significant sequences by Analytics. By feeding the network with relevant data about the anomalies extracted by local intelligent agents and by sharing the information at every level, the resulting AFDD system becomes a distributed computing application.**

Keywords*— *Digital Twin, Facility Management, Predictive Maintenance, Internet of Things, Building Information Modeling

I. Introduction

The recent technological advancements, as well as the development of emerging paradigms such as the Smart Cities, Internet of Things (IoT) Platforms, and Big Data Management, are allowing for novel possibilities in terms of cognitive and decision-making processes relevant to the management of building facilities [1].

With the aim of supporting data integration but, more importantly, enabling integration and collaboration among facility managers (FM) decision makers, the idea of an IoT Platform is growing rapidly these days, as it can provide a unique and integrated framework for data storage, analysis, and retrieval, as well as advanced service management that accepts the concept of centralized data [17]. IoT Platforms, allow FM and real estate managers to benefit from an open IoT environment that allows for the convergence of various technologies (building management systems, sensors, and connectivity), resulting in more smart building management. In general, IoT adoption, helps FM operators to recognize and apply new advanced techniques [18].

According to authors of [2,3], poorly managed, degraded, and poorly operated machinery wastes between 15% and 30% of the electricity used in commercial building systems. However, most of this waste could be avoided if automatic condition-based maintenance were widely adopted. As the foundation for condition-based management of physical systems can serve automated fault detection and diagnostics (AFDD). In the majority research cases of the building facility management, AFDD is implemented in heating, ventilation and air conditioning (HVAC) systems or more specifically in air handling unit (AHU) and fan coil units (FCU) of building. Over the last few decades, extensive study in the field of AFDD has been undertaken to classify various techniques that are appropriate for building HVAC and AHU systems by authors of [4,5]. They applied physical redundancy, heuristics or statistical bands, including the control chart approach, pattern recognition techniques, and innovation-based methods or hypothesis testing on physical models to detect faults. To isolate faults authors are utilized information flow charts, expert systems, semantic networks, artificial neural networks, and parameter estimation methods. A number of AFDD products, including software and hardware, have been or are being produced as a result of the study. However, assessing various AFDD systems' reliability is a challenging task, and developing a more reliable AFDD system for building facility management involves professionals and practitioners from different areas to work in collaboration [6, 7].

Similar studies have already been published [14, 15], in which some authors describe building monitoring and diagnostics using websites. They implemented various sensors to monitor building facilities and incorporated IoT sensor data to monitor internal building conditions.

The abovementioned works have a drawback in that they do not deliver information about building facility faults on the BIM model, which can be useful for further maintenance services provided by operators.

Furthermore, FM operators continue to rely on paper maintenance and control sheets, which increases both the time necessary for compilation and processing of information [16]. As a result, the development of a streamlined and technology-integrated workflow methodology is important for the improvement of FM processes.

This paper describes methodology to monitor the condition of the FCU and proposes AFDD approach to detect faults. Integration of sensors on each element of the

FCU and identifying common faults of each FCU component are indeed part of developing an AFDD approach using real-time data. Furthermore, collected data from sensors are integrated to the Building Information Model (BIM). A Digital Transformation then implemented by linking the data collected real time from the sensors with a dashboard for trend visualization. The BIM model is used to visualize the position of the element and have an overall view of the building.

The paper is organized as follows: after introduction, faults detection methodology on local sensor node is introduced, and then IoT based fault diagnostic approach is described, and reproduced network of sensors on the BIM model is presented, and finally conclusion and future works are summarized the paper.

II. FAULT DETECTION METHODOLOGY BUILT ON LOCAL SENSOR NODE

In order to diagnose the faults, the procedure reported in Fig.1 (at the end of the paper) in form of Business Process Model and Notation (BPMN) diagram is followed [9]. Sensors are positioned at the top level of the maintenance process as input data for the management system layer. The fault detection system can identify various failures based on the data collected from FC components. The most typical FC system faults include a blocked motor, insufficient airflow, unclean filters, capacitor failure, insufficient water flow and so on. Each of these faults requires appropriate action.

On the last layer of the maintenance process, operators must perform maintenance tasks such as cleaning the filter and battery, changing bearings, replacing capacitors, and checking valve adjustment, and the presence of pipe sediments. To detect automatically faults in the construction systems, building facilities must be equipped with sensors.

One of the important facilities of the building is fan coil unit (FCU) that is part of the heating ventilation air condition (HVAC) system that uses coil and a fan to heat or cool rooms of the buildings. As a case study, fan coil model FC83M - 2014/1 with a 3-speed (high, medium and low) version has been used. The FC has motor that produces 1100 revolutions per minute (RPM) in an anti-clockwise direction. Furthermore, FC has a cooling and heating battery and filters that must be often monitored.

To develop sensor-based fan coil monitoring and automatic fault detection system, specific sensors are required. The measuring parameters and measuring ranges of the sensors differ depending on the internal components of the fan coil. Considering this features, specific sensors and sensor board that hosts all sensors are selected for this project and described in Table 1.

TABLE I. SENSORS SPECIFICATIONS

Sensor node	Sensor name	Variable	Range	Acc.	Unit
RPIZCT4V3T2 (Raspberry Pi Zero W and Arduino MCU)	Current SCT-013-000	i1, i2, i3	0-100A	±3	A
	Voltage 77DE-06-09	v1, v2, v3	0-230 (50Hz)	±5	V
	Temperature DS18B20	T1, T2, T3, T4	0°–90°C	±0.5	°C
	Temperature RTD(PT100)	T5	-200°-550°C	±0.05	°C

TABLE II. SENSORS SAMPLING FREQUENCIES

Sensors	Frequency	Sensor allocation
T1	180"	delivery pipe
T2	180"	return pipe
T3	180"	air intake
T4	180"	air outlet
T5	10"	motor case
v1, v2, v3	0,1"	motor voltage (speed I, II, III)
i1, i2, i3	0,05" / 3"	Motor currents (speed I, II, III)

Furthermore, sampling frequencies of sensors are important not to lose important features while storing operating data to the database. Configured data acquisition sampling frequency of each sensors are listed in Table 2.

To demonstrate the applicability of the fault detection system all the above-mentioned local sensors were connected to the RPIZCT4V3T2 embedded system and to the FCU in order to acquire conditional data as shown in Fig. 2. On the sensor board, temperature sensors T1, T2 and T4 measure condition temperature in the range between 0°– 90°C. T3 is responsible to measure the air temperature in the range 0°–50°C and T5 is attached to monitor the motor case and measures in the range between 0° to 200°C. Voltage and current sensors are connected to the power line of the fan coil to monitor the behavior of the motor in three speeds. The RPIZCT4V3T2 embedded board is programmed in such a way that coming data from sensors are sorted according to the importance of the data and stored to the local or cloud database.

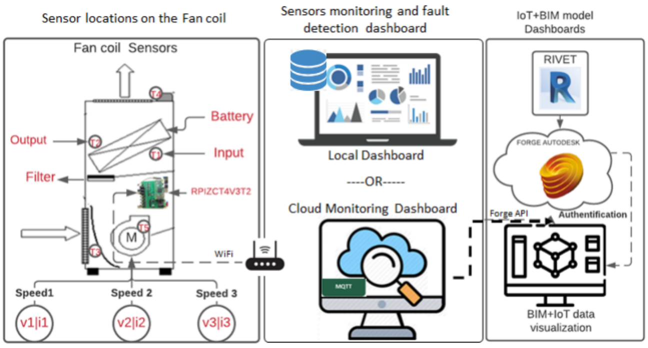

Fig. 1. Fault detection system composed of fan coil with installed sensors, local and cloud monitoring and fault detection dashboard and IoT and BIM 3D model integrated dashboard.

The RPIZCT4V3T2 board composed of an Arduino microcontroller (MCU) that is connected to the temperature sensors. Current and voltage sensors are connected to the MCU through amplifier and analog to digital converter (ADC). Additionally, on the RPIZCT4V3T2 board, MCU connected to the Raspberry Pi (Rpi) Zero W via general purpose input output (GPIO) pins. RPi Zero W is single board computer with integrated Wi-Fi module. The board is programmed to collect raw data from sensors and MCU computes necessary values and sends the final computation to the Rpi Zero W using Universal Asynchronous Receiver-Transmitter (UART) serial port.

On the Rpi Zero W, Node-Red is installed that provides the possibility to access the variables of the sensors through serial protocols and displays on its own local dashboard. MQTT flow on the Rpi Zero W is responsible for sending (Publishing) a message to the cloud server which will act as a receiver (Subscriber) using Message Queue Telemetry

Transport (MQTT) protocol. MQTT protocol is an OASIS standard messaging protocol for IoT. It is designed as an extremely lightweight publish/subscribe messaging transport that is ideal for connecting remote devices with a small code footprint and minimal network bandwidth [8].

Moreover, DNSmasq free software is installed to use the Rpi Zero W as a router and to provide a communication bridge between internal sensors and external components using internet protocol (IP) addresses.

To store sensor data locally on the Rpi Zero W, MySQL database, PHP interpreter, and Apache web server are utilized. Connection diagram between components and sensors of the local fault detection system based on RPIZCT4V3T2 board is depicted in fig. 3.

While running the system all sensors start to collect data from the fan coil and end-user can access to the Rpi Zero W using static IP address of the board.

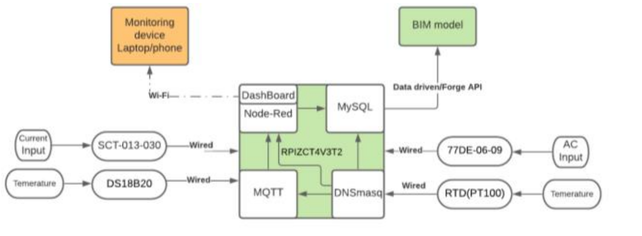

Fig. 2. Connectivity diagram of the RPIZCT4V3T2 with sensors and components.

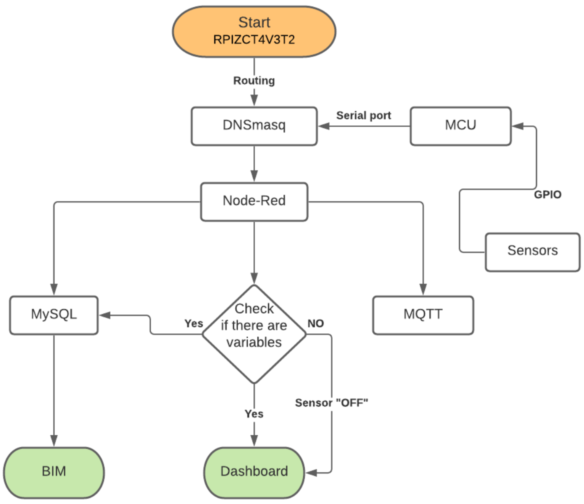

Fig. 3. Connectivity diagram of the RPIZCT4V3T2 with sensors and components.

On the board Node-Red and MQTT provide access to the external devices. By powering the Rpi Zero W, MySQL gets the IP address and opens the configured port and waits Node-Red to send data that must be collected and allocates to the linked tables. Collected MySQL data can be connected to the BIM using data driven approach or directly using Forge nodes on the Node-Red.

Using developed extensions on the Visual Studio Code for Autodesk Forge Viewer, collected IoT data and 3D building model of Revit can be visualized together on the Forge Viewer using URL and PORT provided by Forge API. Fault detection system connectivity diagram with sensors and related components are shown in Fig 4.

Fan coil condition monitoring dashboard has been realized on the Rpi Zero W Node-Red graphical user interface(GUI). Node red flows created to develop a fan coil dashboard. Using serial port node, sensors data coming to the MCU is registered as a string. Developed functions on the Node-Red flow, split and convert data coming from serial port into the dashboard. Fig. 5 shows fan coil monitoring flow on the Node-red.

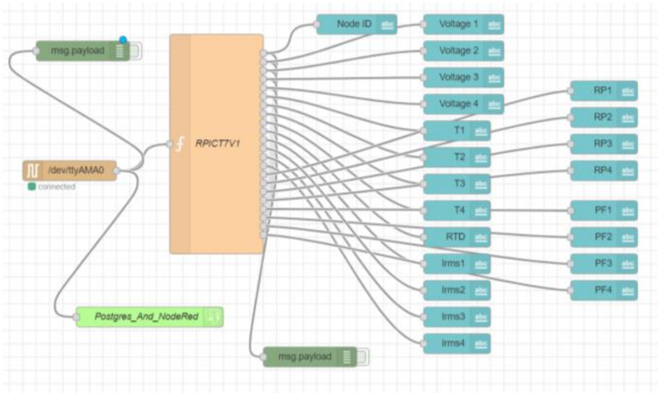

Fig. 4. Node-red monitoring flow of sensors data acquisition.

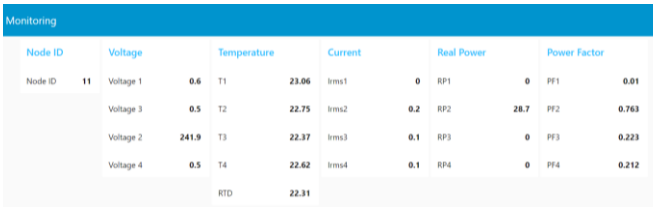

Fig. 5. Node-Red dashboard with measured parameters.

The results of the fan coil real time monitoring dashboard are shown in Fig 6.

To test the dashboard one voltage(V2) and one current(I2) sensor to the second port of the board and all temperature sensors including RTD are placed to the fan coil. The fan coil and sensor board data acquisition system are shown in Fig 7.

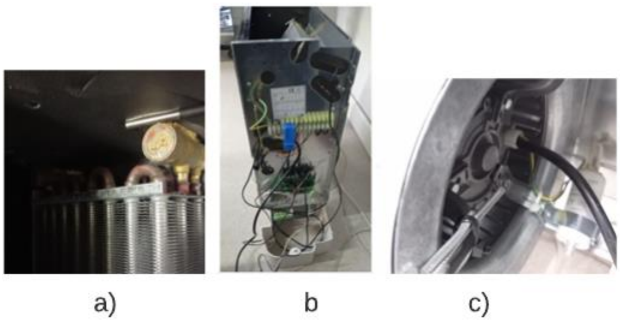

Fig. 6. Sensor board integrated to the real case fan coil: a) return water monitoring temperature(T2) sensor attached to the battery; b) RPIZCT4V3T2 board attached to the fan coil; c) temperature(T5) sensor attached to the motor of the fan coil.

III. FAULT DIAGNOSTIC THROUGH IOT

The proposed framework was tested on fan coils in selected rooms in a University building with connected sensors. The case study was run at the Politecnico di Torino in the DISEG Laboratory. The FC sensors were linked to the set up speed and each time the speed was adjusted. The final result of the rooms' dashboard with physical parameters acquired from sensors are shown in Fig. 8.

Fig. 7. Node-Red dashboard values coming from ESP8266 sensor node in the room.

Fan Coil Monitoring

Node ID		Voltage		Temperature		Current		Real Power		Power Factor	
Node ID	11	Voltage 1	244.1	T1	23.03	Irms1	0.1	RP1	32.3	PF1	0.899
		Voltage 3	0.3	T2	28.37	Irms2	0.1	RP2	0	PF2	0.15
		Voltage 2	0.2	T3	23.62	Irms3	0.1	RP3	0	PF3	0.115
		Voltage 4	0.3	T4	24.81	Irms4	0.1	RP4	0	PF4	0.183
				RTD	23.37						

Fig. 8. Sample of Node-Red dashboard values coming from on-board sensors at the lowest FC speed.

In Fig. 9 all the sensors' data coming from the FC at one of the possible speeds are displayed on the dashboard.

The presence of the faults is monitored through a set of sensors. Particularly, five temperature sensors are available (T1 for delivery water temperature, T2 for return water temperature, T3 for inlet air temperature, T4 for outlet air temperature, T5 for motor casing temperature), three voltage sensors are available (v1 for power supply voltage at motor speed 1, v2 for power supply voltage at motor speed 2, v3 power supply voltage at motor speed 3), and three current sensors are available (i1 for current absorbed by the motor at 1 speed, i2 for current absorbed by the motor at 2 speed, i3 current absorbed by the motor at 3 speed).

IV. REPRODUCING THE NETWORK OF SENSORS ON THE BIM

The sensor board memory is not sufficient for the data storage at the selected input rate. Therefore, to avoid overloading the local memory of the sensor board, only daily maximum and minimum variables and detected faults are recorded and sent to the cloud and BIM server. Fault detection diagram described in previous section is integrated to the system [10], [11].

If the coming values from sensors over the configured ranges, the system sends alarms signal or notifications to the end-user facility managers in real-time.

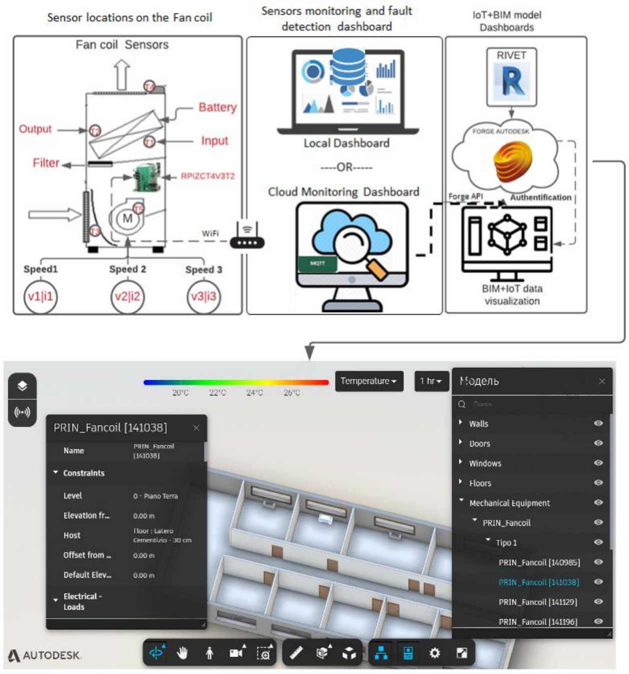

Fig. 9. BIM model with real time monitor of FCU conditions

To support facility managers, conditional data of the FCU has been transported to the BIM model of the building [12], [13]. To visualize conditional data of the FCU on the 3D model of the building, sensors data are implemented to the BIM using Forge Reference Application and two NPM modules (React UI components and Client-Server Data-Module-Components). Final custom application IoT and BIM developed on the JavaScript and Forge Platform is shown in Fig. 10. The application supports heatmap function which changes color of the 3D model of the fan coil according to the data coming from sensor board. The color is "green" if the fan coil in good condition, "red" if overheated, and "blue" if the fan coil is cooling.

V. CONCLUSIONS AND FUTURE WORK

In this paper, the IoT sensor platform and AFDD methodology to monitor the condition of the FCU and to detect faults are presented. Basic IoT platform is a part of the building AFDD system that contains sensors that are installed to the FCU, wireless sensor node that continuously sends received data through gateway to the local and cloud servers accordingly configured sampling frequencies.

When an anomaly occurs, the proposed anomaly detection algorithm is integrated on the server using Node-Red flows, sends warning signals to end-user managers.

On the 3D model of the building, the BIM and IoT integrated technology is developed to track the state of the building facilities. The application is designed on the Autodesk Forge platform, which offers API services for BIM and allows users to create custom web apps in the cloud.

The proposed framework's final findings, which include an IoT sensors dashboard, an IoT and BIM combined program, and a server-based preventive maintenance methodology for building facilities, demonstrate the framework's applicability.

Future studies will aim to leverage data obtained from the proposed fault detection system for predictive building facility maintenance. Artificial intelligence (AI), especially machine learning (ML) tools and algorithms should be employed for facility predictive maintenance systems. The final results of the decision support systems will be used in augmented reality systems to demonstrate to facility managers and operators which part of the building facilities has a failure or anomalies.

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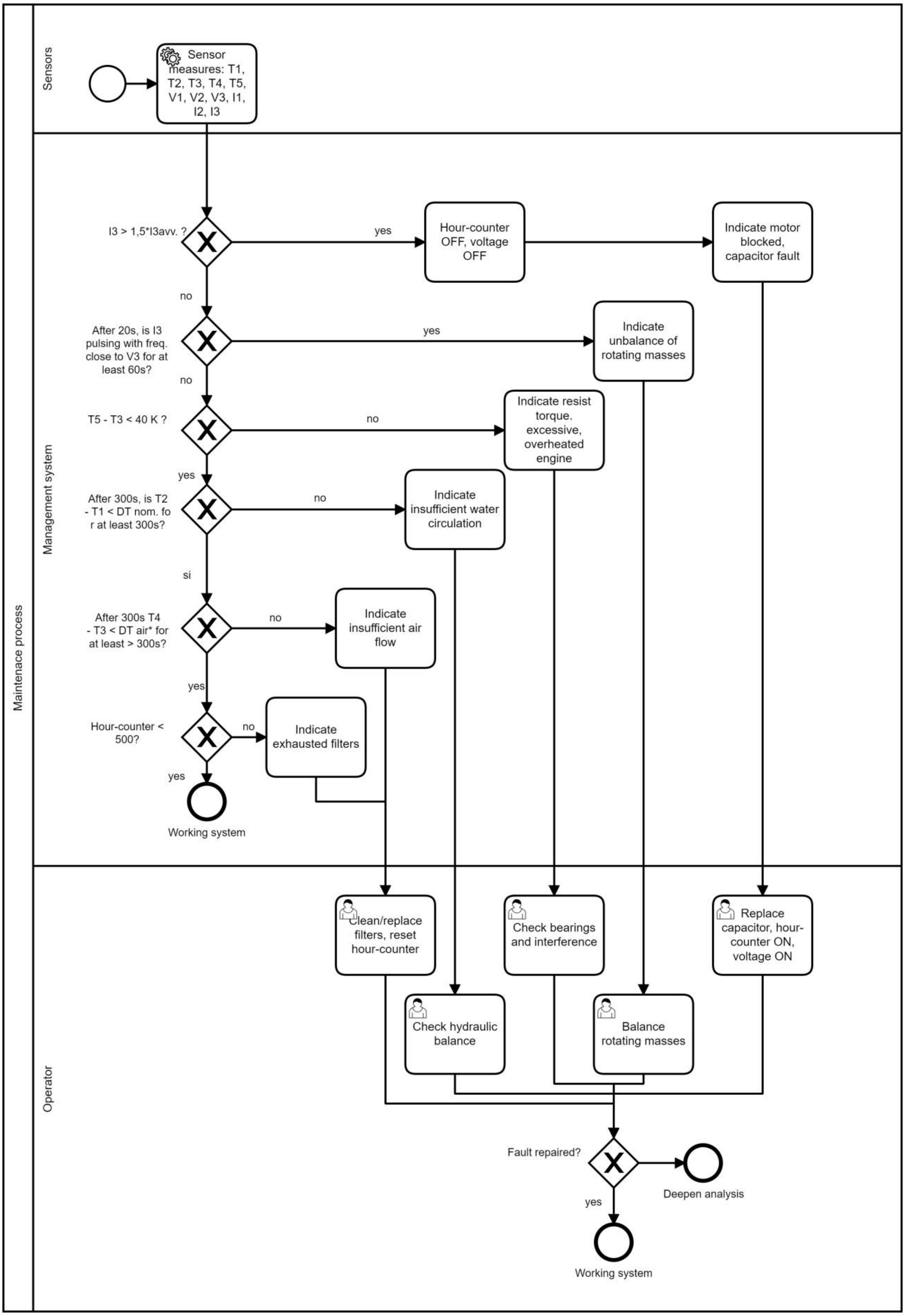

Fig. 1. Fault detection diagram of the system.