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Failure analysis of a smart sensor node for precision agriculture

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***Abstract* – Nowadays, the use of big data analysis and IoT (Internet of Things) technologies is growing tremendously within companies and organizations in several different application fields. In this scenario, smart farming refers to monitoring of environmental conditions and soil parameter to improve farm productivity, to optimize soil conservation, to save water and to limit plant diseases. During the design of such innovative IoT technologies it is fundamental to carry out a reliability and failure analysis of the device. This could allow to introduce adequate diagnostic solutions to improve the system's availability. In this work, a failure analysis using FMEA (Failure Modes and Effects Analysis) approach of a smart sensor node for precision farming has been developed. The results of the analysis allow to improve the design of the device introducing a diagnostic-oriented prototype able to solve the major criticalities arisen during the FMEA.**

Keywords – FMEA; Diagnostic; Reliability; Smart farming; Wireless Sensor Network; Zero Hunger.

I. INTRODUCTION

Precision agriculture refers to a farming management concept based on observing, measuring and responding to crop variability, atmospheric variation and soil status. The major goal of precision agriculture is to define a decision support process able to optimize the crop and minimize waste of resources, with a major benefit on the whole farm management [1]–[3].

Wireless Sensor Network (WSN) are becoming of fundamental importance in the precision agriculture research because they allow multiple monitoring of several quantities covering extended areas [4]. Wireless sensor node for agriculture applications must satisfy the following requirements [5], [6]:

- Low cost: this will allow the installation of several platforms within the same field ensuring a dense and distributed monitoring of the crop.
- Low power consumption: since the node are usually self-powered with batteries and small photovoltaic modules, the minimization of power dissipation is essential to guarantee a maintenance interval as long as possible.
- Fast multi-sensor acquisition: it is necessary to acquire data coming from several sensors, such as air temperature, air percentage humidity, soil temperature, soil moisture, solar radiation, wind speed and direction, air quality, and many others.
- Fast and robust communication: most of the times in case of vast monitoring areas, the sensor nodes not only acquire data, but they also must serve as bridge for the other nodes. Thus, a fast and robust communication infrastructure is required to avoid missing information.
- Reliable unit: Usually, due to size and cost constraints, functional redundancies are not allowed in this kind of platforms. Thus, it is essential to guarantee high reliability of the device since, in case of failure, the availability of the entire architecture could be compromise.

The fulfilment of the entire above-mentioned set of requirements is not always easy to achieve. One of the most critical point is played by the system reliability. As a matter of fact, sensor node for precision agriculture are low-cost devices that are installed in outdoor environment. Most of the times, they must endure severe external stressful conditions that have a negative impact on electronics' reliability [7]. Examples of external factors with a major impact on system reliability are thermal variations, climatic shocks (i.e., extremely cold or extremely hot temperatures), high humidity, atmospheric shocks (i.e., heavy rain, hailstorm, etc.), mechanical shocks induced by the wind or by wild animals, and many others [8], [9].

A failure analysis could provide an essential help during the design phase of a new product, pointing out the major criticalities of the device and proposing countermeasures to increase system's availability [10]–[12]. In this regard, this paper presents a failure analysis of a customized self-developed smart sensor node for agriculture applications based on Failure Modes and Effects Analysis (FMEA). The results of the analysis are then used to introduce a diagnostic-oriented prototype able to overcome the major criticalities found during the FMEA ensuring a risk mitigation and an increased system's availability.

The rest of the aper is organized as follow: section II briefly discusses about the basic concept of FMEA, section III describes the device under analysis, while section IV introduces the innovative diagnostic-oriented sensor node.

II. FAILURE MODES AND EFFECTS ANALYSIS

A functional failure analysis is one of the most efficient and effective tools used for risk assessment and maintenance management. Within the context of failure analysis, Failure Modes and Effects analysis (FMEA) plays a central role in several different industrial and technological field since it is a structured and systematic procedure which allows to identify the criticalities of a system [13], [14].

FMEA is a standardized procedure for qualitative risk assessment described in the international standard IEC60812 (last update 2018) [15]. When FMEA is performed during the early phase of the product design it allows to identify the most critical risk events and propose countermeasures to mitigate it.

FMEA worksheet includes the system decomposition according to the different hierarchical levels and a list of possible device failure modes for every item and every subpart included in the device. Furthermore, failure causes must be identified for every failure mode included in FMEA, as well as failure effects. Usually, failure effects are classified according to their level of impact, as local and global/final effects. The former refers to the impact that each failure has on the same-level items, while the latter describes the consequences of the failure mode on the entire system, on the users/personnel and on the environment.

The final part of FMEA worksheet includes some recommended corrective actions to improve the design and minimize the risk associated to each failure. Some common countermeasures refer to the use of higher-quality components, the introduction of active or standby redundancies, improvements on the personnel training procedures, and many others. Among all of them, a valid and powerful solution is the introduction of diagnostic devices able to monitor the health state of components/systems and acquire information regarding the presence of an incoming failure mode. Such devices (see for instance but not only [16], [17]) must be designed properly in order to be able to detect the failures prior that their effects are manifested on the system. In such cases, it is possible to maximize the availability of the system, with significant benefits on the entire life cycle cost.

For more information regarding FMEA process, advantages, drawbacks and applications, see the following references [15], [18], [19].

III. DESCRIPTION OF THE SYSTEM

In this work, an hybrid-mesh topology network [20] is proposed to monitor environmental conditions and soil parameters in an olive groove. The network is a two-layer architecture that uses multiple stand-alone stations (called sensor nodes) deployed on the field to collect data coming from a set of sensors. The sensor nodes are disconnected from the electric grid, and they are powered using a photovoltaic (PV) panel and two lithium-ion batteries. Once the data have been acquired, the stations transmit them to a specific sink node (also called root node) connected to an Internet access point able to upload data into the cloud as shown in Fig. 1. Each sensor node is a weather-station composed by a power supply (including batteries, Battery Management System - BMS -, PV module and DC-DC converter), a ESP32 system-on-a-chip microcontroller with integrated wireless transceiver, and a set of sensors.

To minimize the energy consumption and ensure a longer life of the nodes, a two-phase working based on acquisition and idle phase has been developed. The complete flowchart of the network functionalities is illustrated in Fig. 2.

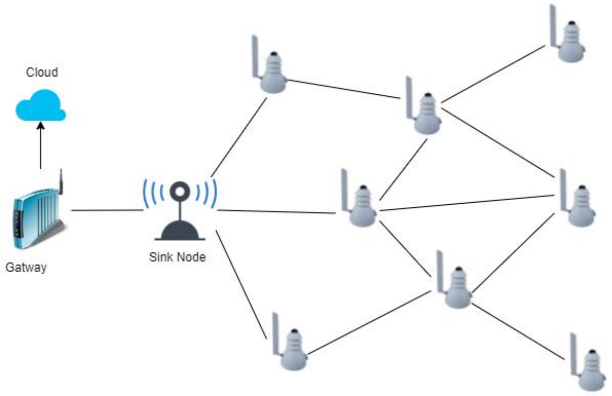

Fig. 1. Architecture of the proposed hybrid-mesh network.

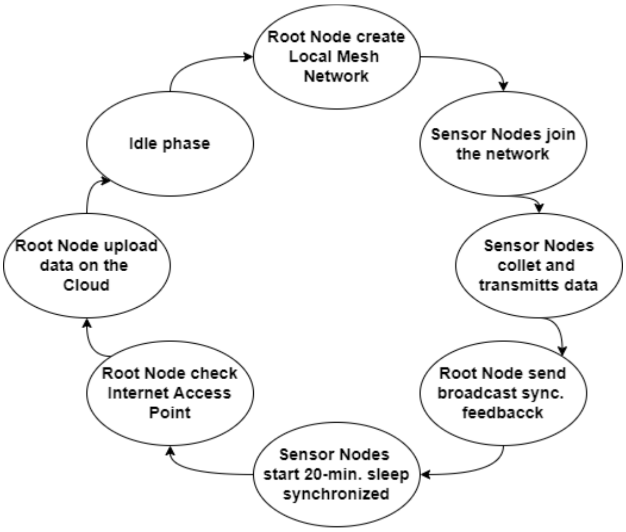

Fig. 2. Different phases of the network working flow.

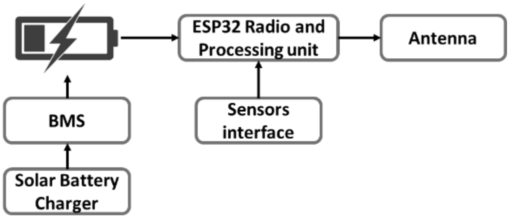

Fig. 3. Block Diagram of the proposed sensor node.

Fig. 4. Picture of the entire sensor node.

A block diagram of the proposed sensor node is illustrated in Fig. 3, while a picture of the device including the PV panel, the external sensors and the waterproof case is shown in Fig. 4.

IV. RESULTS AND DISCUSSIONS

This Section presents the results of the FMEA performed on the network described in section III. An extract of the entire FMEA is reported in Table I, showing for some of the main critical items the failure modes, failure causes and failure effects. The latter have been classified according to three categories:

- Local effects: these are the consequences at subsystem level (i.e., effects on a single weather station).
- WSN global effect: these are the system-wide consequences (i.e., effects on the entire infrastructure) assuming a traditional WSN.
- Hybrid mesh global effect: these are the system-

Table 1. Extract of the FMEA performed on the proposed Hybrid Mesh network for smart farming technologies.

Failure Mode	Failure Cause	Failure Effect			Recommended Action
		Local Effect	WSN Global Effect	Hybrid Mesh Global Effect	
Lithium Batteries - Supply each single station					
Undervoltage	Recharge unit failure.	The station remains off (does not collect/transmit the data).	All stations connected to the root node through the failed station lose wireless connection.	Loss of data from only one station since the network reconfigures itself.	Plan Maintenance Operation
Batteries Imbalance	Bootloader fail leading to over discharge. Incorrect BMS operation.	The BMS monitor different value for the battery and turn-off the station.	All stations connected to the root node through the failed station lose wireless connection.	Loss of data from only one station since the network reconfigures itself.	Balance the Batteries. Parallel configuration.
Bootloader - Program responsible for booting the micro-controller					
The station does not active on demand	Firmware malfunction. Harsh environmental conditions.	µC on loop. No data collected/transmitted. Increment of current consumption.	All stations connected to the root node through the failed station lose wireless connection.	Loss of data from only one station since the network reconfigures itself.	µC Soft Reset.
Wi-Fi unit - Protocol used to join the network and send data					
Wi-Fi transmission fails	Over consumption. Battery voltage drop-out. Software malfunction.	The station does not join the network and does not send data.	All stations connected to the root node through the failed station lose wireless connection.	Loss of data from only one station since the network reconfigures itself.	Manage Battery Life.
Fail to communicate on demand	Harsh environmental condition (i.e. flood and thunder days).	The station does not join the network and loos sensor network sync.	All stations connected to the root node through the failed station lose wireless connection.	Loss of data from only one station since the network reconfigures itself.	Monitor Network Sync.
Root Node - Create and Manage the Network					
Root Node Failure	Bootloader failure. Loss of power supply. HW/SW failure.	No received data.	All stations lose wireless connection.	All stations lose wireless connection.	Redundancy of the root node.

wide consequences (i.e., effects on the entire infrastructure) considering the proposed two-layer hybrid mesh topology.

The analysis of WSN global effect and hybrid mesh global effect allow to emphasize the benefits of the proposed architecture. Indeed, for most of the identified failure modes, the mesh topology guarantees to minimize (or even remove) global effects. However, in case of root node failure, both the network topologies lose all sensors connection. Thus, a redundant root node architecture is mandatory to ensure high network reliability.

Despite the Hybrid Mesh topology guarantee to keep the effects local in most failure modes, in order to increase the network availability and to collect a huge amount of data, some recommended actions are still required. At sensor node level, one of the most critical failures is a Batteries Imbalance which could be caused by a bootloader failure or incorrect BMS. The recommended action for this issue is the use of balancing system or using a parallel battery configuration.

Instead, the Bootloader failure causes an infinite loop condition where the micro-controller is not able to make decision, consuming a higher-amount of power (twenty times greater respect to the idle phase). The only recommended action in this case is an immediate soft reset of the microcontroller.

Finally, few action are needed for reduce failures in the Wi-Fi unit. In particular managing properly the battery life permits to reduce voltage droop-out in high current load spike, while monitor the network sync allows to prevent Wi-Fi transmissions failure.

V. DIAGNOSTIC-ORIENTED PROTOTYPE

In order to solve most of the criticalities arisen in the FMEA analysis (see Table 1), a new diagnostic-oriented prototype has been developed. The design constraints introduced in the diagnostic-oriented solution allow to take into account the majority of the recommended actions in Table 1.

Fig. 5 illustrates the functional block diagram of the diagnostic-oriented prototype, while a picture of the new board is shown in Fig. 6. The main updates introduced in the diagnostic-oriented prototype are the following:

1. Improvement of the power supply unit introducing a Pulse Skipping Modulation based DC-DC converter characterized by higher efficiency as described in [21] to optimize the solar-to-energy conversion and thus improve battery management.
2. Introduction of a micro-USB battery charger system for redundancie purpose. This device will allow fast battery charge during maintenance operarations in case of battery failure.
3. Substitution of the series battery configuration with two-parallel batteries to solve the battery unbalance failure mode. An Ultra-LDO (Low DropOut) regulator ensure the optimal power supply to all electronic devices.
4. Introduction of a diagnostic unit based on the ATmega328P microcontroller which allows to add some diagnostic functionalities to the sensor node, as follow:
    a. It allows to extend batteries life setting a 3 V threshold during battery discharge phase.
    b. It acquires data about the power consumption and temperature of the batteries.
    c. It monitors the main ESP32 microcontroller phases in order to identify failure modes and to implement the recommended action as in Table 1, when needed.

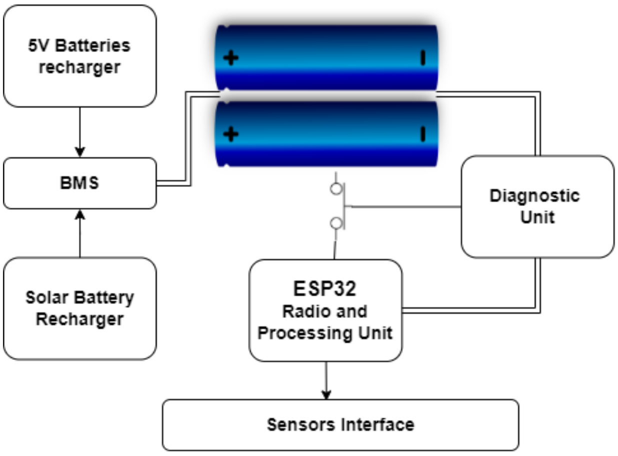

Fig. 5. Functional Block Diagram of the Diagnostic-oriented prototype for the sensor nodes.

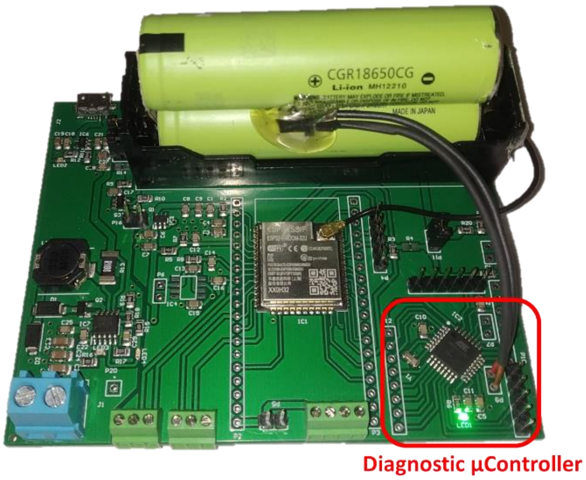

Fig. 6. Picture of the Diagnostic-oriented sensor nodes.

Fig. 7 illustrates the diagnostic algorithm implemented by the ATmega328P microcontroller during all sensor node phases: sleep mode, active mode, data acquisition and data transmission. After the validation of the batteries state-of-charge, the ESP32 microcontroller is enabled to turn-on and to start the data acquisition phase from all the embedded sensors for farming monitoring. The data are validated by ATmega328P through a specific algorithm based on data history and sensors correlation. In case of corrupted data, a "NaN" is transmitted by the main processing unit. Instead, in case of a damaged sensor, the specific sensors will be disabled, and a "need for maintenance" message is sent to the root node. The diagnostic unit validates also the data transmission phase. In case of error, a second transmission or soft-reset is implemented. The cycle finish with a 20 min sleep phase, as required by the major functionality cycle in Fig. 2.

To ensure that network sync cannot be lost and to minimize the active mode time (i.e., to reduce power consumption and save battery life), only one soft-reset is allowed in each operating cycle. Thus, a reset count is introduced to ensure this restriction. The reset count is set equal to 0 every time a new cycle starts.

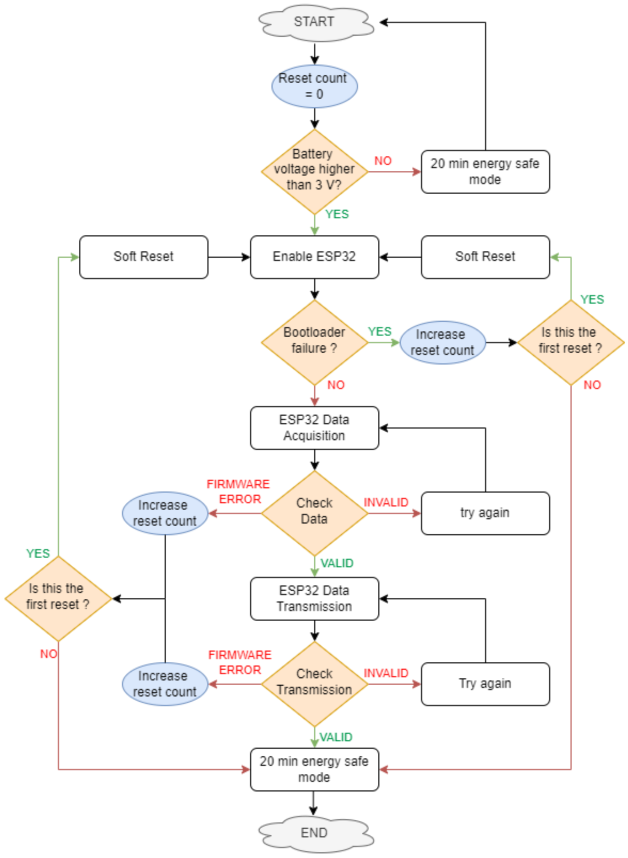

Fig. 7. Functional diagram of the diagnostic algorithm implemented on the ATmega328 microcontroller.

VI. CONCLUSIONS

This work deals with the failure analysis of a sensor node developed to acquire weather information and soil parameters for precision farming technologies. The sensor node is a self-powered device working in the context of a mesh topology wireless sensor network. A FMEA has been carried out to investigate all the possible malfunctions that could affect the device. After the identification of failure modes, failure causes and failure effects, specific recommended actions have been proposed to solve the major criticalities arisen in the study. Finally, a new diagnostic-oriented sensor node prototype has been developed as primary corrective action resulting from the FMEA. The diagnostic unit installed in the new prototype is a ATmega328P microcontroller with a customized diagnostic algorithm able to solve the majority of identified failure modes.

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