IoT ready Eddy Current Testing Structural Health Monitor

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***Abstract*— Non-destructive testing is used to ensure and evaluate the quality and safety of a product, material or system while detecting faults and defects, with the advantage of not causing any damage. Eddy current testing is an electromagnetic and non-destructive method used to identify and assess surface breaking, or near-surface, defects on materials and structures, through detecting discontinuities in segments that conduct electricity. Structural Health Monitoring is one of the applications of non-destructive testing, being a set of systems that gives a continuous and periodic diagnostic of the structure and its parts during its lifetime. To achieve it, the method determines and analyzes all defects and flaws in the structure to be able to provide preventive support and avoid a collapse. To turn the structural health monitoring in real-time monitorization, a platform that supports all remote access to sensorial data and physical devices is being used, named Internet of Things. This work uses a designed electronic system that implements eddy current testing in a structural health monitoring system. The device operates in an autonomous and permanently-mounted and has the aim of reading multiple eddy current sensors, save the data collected and evaluate it. It also connects through a Bluetooth connection with a computer allowing real-time evaluation. The device is hardware ready for future communications using Narrowband-IoT Low-Power Wide Area Network type communication, and to report alarms previously deliberated directly to the cloud.**

Keywords*— *Non-Destructive Testing, Structural Health Monitoring, Eddy Current Testing and Internet of Things.

I. INTRODUCTION

Non-destructive Testing (NDT) is the principal method for inspection used in metallic parts and welding joints. This procedure is due to its viability and capability of not changing the product that is being inspected, saving money and time in evaluation, damage assessment, and research. Some types of NDT methods are radiography, magnetic particle crack detection, dye penetrant testing, ultrasonic flaw detection, and eddy currents and electro-magnetic testing [1].

Eddy Current Testing (ECT) is an electromagnetic and non-contact method used to identify and assess surface breaking or near-surface defects on materials and structures, through detection of discontinuities in segments that conduct electricity. Eddy currents, also known as Foucault currents, are electrical currents induced when a conductor experiences a change in the intensity or direction of a magnetic field. Whenever these currents interact with an obstacle, for example a crack, the current in the vicinity becomes distorted.

Structural Health Monitoring (SHM) is essential, not only to monitor and maintain structures, but also to preserve infrastructures and buildings' integrity, with the goal of ensuring the safety of human beings. SHM makes part of a group of nondestructive evaluation techniques used to monitor the security of structures, which brings benefits such as improving safety standards, detecting early reliability risks, longer structural life spans and reducing costs. To accomplish this improvement there are new guidelines and policies to ensure safe building and construction, as well as new technologies that facilitate security control, such as instrument supervising and testing of digital information about infrastructure security that is being studied. The advances in SHM, like the use of sensors, collection of data on demand and its analysis, promote engineers' capacity of contributing to public safety, which has key importance with a growing number of aging structures. One of the advantages of these advances in SHM is the ability of helping professionals to detect potential risks to a structure safety, for example damages provoked by failed pipelines and other structures that transport water (e.g. in dams), through the use of sensors that monitor the modifications in water levels and are able to detect earlier leaks in infrastructures. Other example is the ability to identify ground movement, such as earthquakes and other disasters, preventing or diminishing huge structural risks created by them. One consequence of the frequent monitorization and maintenance of structures and buildings, by installing sensors and complement technology that provides details relatively to the health of a structure, is an increase in their life span. With the progress of technology, new methods also provide more accuracy and reliability on data collection and analysis. SHM creates a real-time analytical method that itself also allows more accuracy in monitorization and risk analysis. Cost efficiency is, as well, an important reason that justifies its use as with improved maintenance of the buildings, the number of infrastructures that will suffer demolition and expensive massive rebuilding is smaller.

Internet of Things (IoT) refers to a concept of a diversity of objects, such as sensors, mobile phones, radio frequency identification (RFID), etc. These objects are capable to interconnect with each other, and, because of that, create an enormous network where all items are connected through the Internet. In this way, it is possible to complete information transmission, plan and process to allow systems to identify, locate and monitor objects in real-time. Combining SHM with IoT permits the collection of critical structural health specifications with rapid response, off-loading computational power, store data, and remotely monitoring.

The main objective of this work is to make a device capable of implementing ECT in a SHM approach, which can be installed and operate in an autonomous and permanent way while monitoring a structure. This system is able to read multiple eddy current sensors, save the measurements and then analyze them. If needed, the system will generate alarmistic concerning the presence or growth of the monitored fault. It also contains a wireless link to complete interconnection with a computer, granting the collection of preserved data and real-time operation/monitorization. The utilization of a Low-Power Wide Area Network (LPWAN) type communication, in particular, Narrowband-IoT (NB-IoT), will allow the device to report the alarms previously deliberated directly to the cloud.

II. State of the Art

A. Non-Destructive Testing

NDT is a set of non-invasive inspection techniques which purpose consists of analyzing material properties, components and even entirely processed units in a safe, trustworthy and cost-effective way without causing damage. The functionality of these techniques involves also the detection, characterization and/or measurement of damage mechanisms presence. Some NDT techniques can locate defects and determine the features of the detected defect. The more common methods in industry are radiography, magnetic particle crack detection, dye penetrant testing, ultrasonic flaw detection, eddy currents, and electromagnetic testing. Radiography is a technique suitable for the discovery of internal defects in ferrous and non-ferrous metals [2] and magnetic particle crack detection is suitable for the detection of discontinuities in magnetic materials [3]. On the other hand, the dye penetrant testing is used to determine the breaking flaws in non-ferromagnetic materials [4] and the ultrasonic flaw detection is used for the discovery of defects in sound conducting materials [5]. These techniques have some disadvantages which can be observed in Table 1. Finally, the eddy current testing is used for detecting flaws, conductivity measuring and coating thickness measuring [6].

Table 1 - Disadvantages of some non-destructive techniques.

	X-rays	**Ultrasounds**	**Penetrant liquids**	**Magnetic particles**
Expensive	x			
Safety hazard	x			
Time consuming			x	x
Require operator				
Skill and integrity	x	x		
Difficult interpretation of results		x	x	x

B. Eddy Current Testing

The NDT used in this work is the ECT. The scientist who was credited for discovering eddy currents was the French Jean Foucault, in 1855, by building a device that used a copper disk moving in a strong magnetic field showing that eddy currents' generation is due to a moving object within a continuous magnetic field. Nowadays, there was a great evolution in non-destructive techniques, in particular eddy current testing [7], being this type of non-destructive technique widely used performing quality control tests. The major advances that contributed to the development of eddy current testing were the evolution of the micro and nano-electronics field, as it was made possible to build microprocessors with much power, reduced cost and high precision analog to digital converters. As a result, it is possible to make real-time processing in portable battery-powered devices which can show resultant information to a user through a display [8].

Faraday's induction law and Ampère's law are the base of the eddy currents phenomenon. As stated with Ampère's law, the integral around a closed path S of the component of the magnetic field B tangent to the direction of the path is

$$\oint_S \vec{B} \cdot d\vec{S} = \mu I \ , \qquad (2.1)$$

where μ is the permeability of the medium and I is the electric current that flows through the surface bounded by the closed path. Through (2.1), it is possible to determine the magnitude of the magnetic field formed around a wire in a direction perpendicular to the one of the flowing currents, knowing the distance r from it, by

$$B = \frac{\mu I}{2\pi r} \ . \qquad (2.2)$$

According to Faraday's law, when a magnetic flux through a surface bounded by a conducting path has some change, a non-electrostatic electric field is induced and being equal to the electromotive force induced in the wire with a magnitude equal to the rate of change of the flux, as proved in

$$\varepsilon = \oint_c \vec{E} \cdot d\vec{l} = -\frac{d\Phi_B}{dt} \ , \qquad (2.3)$$

where

$$\Phi_B = \int \vec{B} \cdot d\vec{A} \ . \qquad (2.4)$$

Conventional eddy currents technology uses a probe comprised by a coil that, when excited with an alternating current, creates a magnetic field (in blue) represented in Figure 1 (a). When the coil is positioned over a conductive part, opposite alternating currents are created, Figure 1 (b) (red), named by eddy currents. Moving the coil over the homogeneous material, the impedance value of the coil remains constant, however if there is a defect in the material the path of eddy currents is disturbed (in yellow) (Figure 1 (c)) and the magnetic field created is less intense. As result, with the variation of electric impedance in the probe it allows the defect detention.

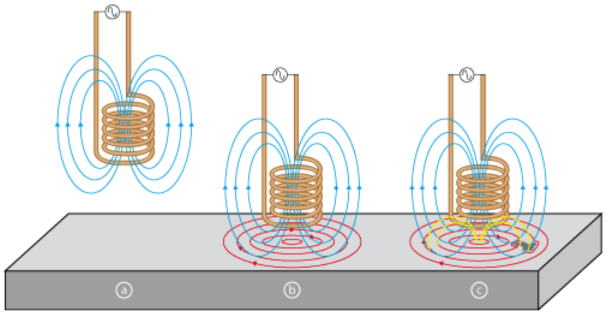

Figure 1 - Eddy Current phenomenon, from [7].

Eddy currents flow is not equally distributed along with the test material depth, it decreases as depth increases. This phenomenon is called skin effect and, as a result, the capability of detecting buried defects is limited. The current density at depth x is

$$J(x) = J_0 e^{-x\sqrt{\pi f \mu_0 \mu_r \sigma}} \ , \qquad (2.5)$$

where J_0 is the maximum value of current density at the conductor surface which corresponds to x=0. The value is null if the operation frequency *f* is also null and it increases as frequency value rises. μ_0 corresponds to the magnetic permeability of free space, μ is the relative magnetic permeability of the material and σ refers to the electric conductivity of the material in the test.

To quantify the depth of detection, the so-called standard depth of penetration is used, this translates the depth at *1/e* (≅36.7%) of the current value measured at the conductor's surface. The standard depth of penetration is shown in Figure **2** and expressed in

$$\delta = \frac{1}{\sqrt{\pi f \sigma \mu}} \, , \qquad (2.6)$$

where δ is the standard depth of penetration, f is the excitation signal frequency, σ is the electrical conductivity of the material, and μ is the magnetic permeability of the material. In Figure 2 is demonstrated that the standard depth of penetration decreases with the increase of the excitation signal frequency, maintaining the electrical conductivity and the magnetic permeability constant.

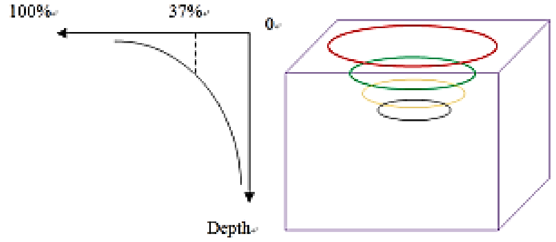

Figure 2 - Eddy current standard depth of penetration **[9]**.

To test with an eddy current instrument a given piece, an eddy current probe is needed. This allows eddy current probes to be classified by configuration and mode of operation of the test coils. The mode of operation of a probe is normally inserted in one of four categories: absolute probes, differential probes, reflection probes, and hybrid probes.

To excite a probe can use a single frequency technique, a multiple frequency technique, a pulsed eddy current technique that uses a periodic pulse to excite the pulse, and the harmonic excitation technique, which in a presence of a defect in the tested material, the amplitude and phase of the electromagnetic field change implying changes, leading to a change in the coil induced voltage.

This method has advantages compared to the others existing, like high sensitivity to detect small flaws and defects in the surface or near it and in a determinate range, with good linearity indication. These sensors can also detect defects through non-conductive surface coating in excess of 5 mm thickness, results obtained almost instantly and the equipment need is portable. To finish, these sensors allow the analysis of the material with no contact with it. The principal limitation of this method is the need of the tested material being conductive and the necessity of the sensor being closed to the surface due to the eddy currents limitation of only existing on the surface and near-surface. The surface in test needs to be polished to avoid interferences to accomplish a correct analysis, and the depth of the measure is limited. Other limitation of eddy current sensors is the high susceptibility to magnetic permeability, this means that a small change in permeability results in a huge effect in eddy current. If the probe is not coupled perpendicularly at the material surface shows an electric impedance variation named lift-off.

C. Structural Health Monitor

SHM implements a damage detection strategy through the observation and monitoring of a structure continuously in order to identify the actual state of the structure. To accomplish that, the system must periodically measure structure's characteristics and then analyze them. SHM can be divided into four categories: machine condition monitoring, global monitoring of large structures, large areas monitoring and local monitoring.

The SHM process usually relies on monitoring a structure over a certain period using suitable sensors to make some measurements and then analyze them to identify the current state of the structure. SHM systems involve a set of processes like measuring and collecting different parameters through sensors, analyze them and finally taking corrective actions.

The first part is the function of monitoring the structure, which can be characterized by the kind of physical phenomenon associated to the damage monitored by the sensor or by the kind of physical phenomenon used to produce a signal sent to the repository sub-system by the sensor. When having various sensors of the same type they form a network and their data is blended with data from other types of sensors. To create a diagnostic, the controller uses the signal delivered by the integrity monitoring sub-system at the same time as the previously data is already registered. To finish, a similar structure management system connected to other structures can be considered a super system, making possible the health management of that super system.

SHM has several advantages such as allowing a longer-lasting use of the structure, a reduced inactivity time, the early avoidance of catastrophic failures increasing safety, better cost efficiency, improvement of constructor's products and changings on maintenance services. Structures with SHM have high reliability and low maintenance costs along with higher lifetime of the structure. The structures without SHM may see their reliability decreased as well as their lifetime and the maintenance costs end up increasing.

D. Internet of Things

IoT is a huge system created by blending network facilities and internet. In this way all components are connected with the network originating a system that can automatically identify, locate and monitor that component in real-time.

The core organization of IoT systems is based in four layers: perceptual layer, transport layer, treatment layer, and application layer. The perceptual layer corresponds to the physical layer, its principal function is to percept, recognize and monitor/collect data from objects. The transport layer is equivalent to the traditional information transmission layer and its primary function is to allow information transmission between the perception layer and the treatment layer. The treatment layer implements intelligent processing of massive information through cloud computing, data mining and intelligent processing. Finally, the application layer is based in the other three layers and it is where IoT completes the unification of information technology and different industries. In this case, the application layer is based in structural monitoring.

For the transport layer case, different wireless protocols are available and can be applied, as different applications require different wireless protocols. Table 2 presents five types of wireless protocols where three different characteristics of each can be observed: operation frequency band, maximum data rate and typical communication range.

Table 2 - Wireless protocols.

Protocol	Operation Frequency Band (MHz)	Maximum Data Rate (kbps)	Typical Communication Range (m)
Bluetooth BR/EDR	2400-2483.5	2100	10
LoRa WAN	Regional sub-GHz bands 433 / 780 / 868 / 915	50	2000 ~ 14000
NB-IoT	LTE In-band, Guard band or Standalone 900	200	~ 22000
SigFox	Regional sub-GHz bands 868 / 902	0.1	3000 ~ 17000
Wi-Fi	2400-2500; 5725-5875	54 x 10^3	30

IoT introduces several advantages such as increasing the acquired information to make better decisions, providing a better tracking system from objects and data, saving time used on the gathering and processing information, and if the cost of tagging and monitoring equipment gets low, the cost of IoT will also become lower. However, IoT has some disadvantages like the lack of compatibility for the tagging and monitoring devices or equipment, the complexity of these kind of systems is huge which increases the chances of failure, the difficulty of providing safety service, and the bandwidth is limited for some applications.

III. Hardware

The final system focuses on monitoring the growth of a crack previously detected on a metallic material of a structure in an autonomous and permanent way. The system architecture used to complete the whole system is presented in Figure 3.

The system is divided into five modules each of which has its own function. The processor module is the one that controls all the device and process all the information gathered through the others four modules, therefore is the more important and indispensable module. The power management module is the one that power the whole system. The environment sensors are responsible for measuring external factors that may provoke changes in the test material. The ECT module receives and converts to digital the data collected by eddy currents sensors. The NB-IoT module enables the report of alarms previously deliberated directly to the "cloud". The hardware organization of the system follows the same division previously mentioned.

A. *Processor*

To process all the data collected from all the sensors previously mentioned a microcontroller is needed, and the chosen is the Espressif Systems ESP32. The benefits of using the ESP32 chip microcontroller rely on having the robustness to face the adversity of surroundings, performing in low-power mode, but also have four more power modes useful when the full usage is not need. It also has an optimal trade-off between communication range, data rate and power consumption, and it is a highly-integrated solution for Wi-Fi-and-Bluetooth IoT applications. All these features make the ESP32 one of best microcontrollers to be included in the system

The ESP32 has forty-nine pins and eight of them are divided into two categories. Starting with the ESP32's digital pins, they are divided into three distinct power domains: VDD3P3_RTC, VDD3P3_CPU and VDD_SDIO.

As said before the ESP32 processor integrates a Bluetooth link controller and Bluetooth baseband, capable of carrying out the baseband protocols and some other low-level link routines. Some of the features that the ESP32 Bluetooth radio and baseband support are a high performance in Zero Intermediate Frequency (NZIF) receiver sensitivity with over 97 dB of dynamic range, a power management for low power application and through the internal Static Random Access Memory (SRAM) allows a full speed data transfer, mixed voice and data. The Bluetooth link controller operates in three major states denominated standby, connection and sniff. It permits several connections and other operations like inquiry and secure sample pairing.

The version of ESP32 chosen is the ESP32 D2WD with a FLASH size of 4 Mbytes. The processor is clocked at 26 MHz through a crystal oscillator connecting its outputs to the XTAL_N and XTAL_P pins of the chip. The antenna selected to allow the wireless connection between the host was adapted from the module ESP-WROOM

B. *Power management*

To power the system, buck-only converters are the chosen ones. A buck converter is a switched DC-DC power converter

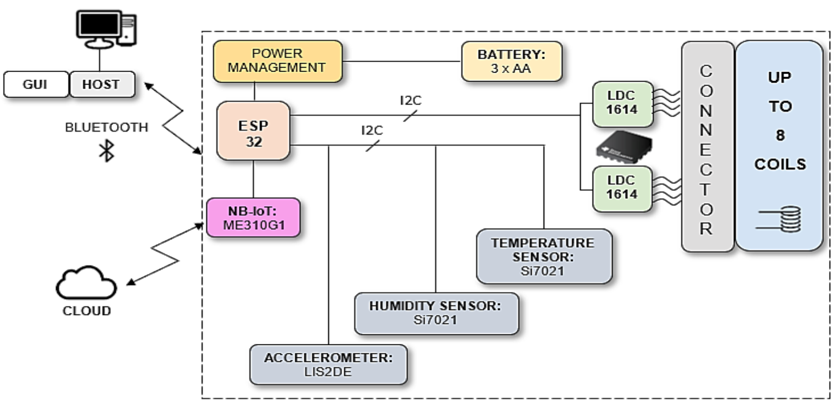

Figure 3 - System architecture.

that steps down voltage from its input to its output. The Diodes Incorporated AP3428 is a switching regulator and it is the part selected allowing a maximum of 5.5V power supply and sets the output to approximately 2.6 V. An important note is that this is the power supply being active while the main processor is awake, and it has a good efficiency when the output current is high. When the main processor is asleep, the fallback power supply is ensured by the Diodes Incorporated AP2138N 2.5 LDO voltage regulator whose output is fixed to 2.5 V. An LDO regulator is a DC linear voltage regulator which is able to regulate the output even if the supply voltage is really close to the output voltage. This has a better consumption when the output current is lower. To avoid leakage through the LDO pass device, the LDO output voltage has to be lower than the buck converter output voltage. An additional circuit to avoid leakage current through the buck converter is required. This circuit is the transistor (Q1) and the respective gate control circuit. This transistor enters cutoff preventing current to flow through the DCDC output and feedback branches, when the buck converter enable signal DCDC_EN is de-asserted.

It was chosen a set of three batteries of AA size with 1.5V each totalizing 4.5V. The choice of this method to power the system is justified by the need of a low power, portable and small source to power the device

C. Environment sensors

To analyze the environment where the structure to monitor is placed, three indicators were selected: temperature, humidity and acceleration. To collect the temperature and relative humidity of the environment where the system is placed, the sensor of Silicon Labs Si7021 is chosen. The Si7021 provide a low-power, high-accuracy, calibrated and stable solution optimal for applying to an ample range of temperature, humidity, and dew-point applications.

Si7021 integrates humidity and temperature sensor elements with an analog to digital converter (ADC), signal processing, data calibration, polynomial non-linearity correction and an Inter-Integrated Circuit (I2C) interface. The calibration data, from its individually factory-calibration from temperature and humidity, is stored in on-chip non-volatile memory. This feature guarantees a full interchangeability with no need to recalibrate or change. This sensor has a low power consumption which is an important feature to this application, since the main function of it is not required at all times and the device is meant to be battery powered. Si7021 has a wide operating range both relative humidity and temperature. The relative humidity operating range is from 0 to 100 % and the temperature operating range is from -10 to 85 ºC, with ± 0.4 ºC of accuracy.

LIS2DE12 can also collect the temperature value, however it is used only to measure the acceleration or the vibration the system is being subject of the system. The entire measurement chain converts the capacitive unbalance of the Micro Electro-Mechanical Systems (MEMS) sensor into an analog voltage through a low-noise capacitive amplifier. The process is completed with the transmission of data through an I2C interface. It has multiple full scales to be selectable of ±2g/±4g/±8g/±16g and can measure accelerations with output data rates from 1 Hz to 5 Hz. In this application we choose the ±2g full scale and 400 Hz data rate. A ±2g full scale is chosen, because in a normal application scenario the device will work coupled to a static installation. In this case scenario, the static acceleration will have a maximum of 1g on the possible axis. The dynamic acceleration, added to static acceleration, will be low because the installation has no movement. This scale allows to have the best resolution possible with the 8 bits of the application ADC. The LIS2DE12 sensor embeds a 10-bit wide, 32-level FIFO. FIFO, Stream, Stream-to-FIFO and FIFO bypass are the four operation modes allowed due to buffered outputs. If FIFO bypass mode is activated, FIFO remains empty and do not operate. However, if the FIFO mode is activated, measurement data from acceleration sensing detection on the x, y, and z-axes are stored in the FIFO buffer.

D. Eddy current testing

The ECT module includes two four channels Inductance-to-Digital Converters (LDC) so that the device be able to read up to eight coils. The chosen one is the Texas Instruments LDC1614. The function of LDC1614 is to measure the oscillation frequency of multiples LC resonators. The output of the device is a digital value proportional to frequency, with a measurement resolution of 28 bits. The frequency measured can be converted to an equivalent inductance, or, instead and depending on the application, mapped to the movement of a conductive piece. The LDC1614 can support a wide range of inductance and capacitor combinations with oscillation frequencies varying from 1 kHz to 10 MHz with equivalent parallel resistances as low as 1.0 kΩ.

The functional principle relies on having conductive objects in contact with an alternating current (AC) electromagnetic (EM) field that consequently induces field modification detected through a sensor. Surely, an inductor, along with a capacitor, build an L-C resonator, also named L-C tank, capable of producing an EM field. With a L-C tank, the effect caused due to a disturbance is an apparent shift in the inductance of the sensor, that is visible as a shift in the resonant frequency. The LDC measure the oscillation frequency of the L-C resonator. In more detail, it has front-end resonant circuit drivers, pursued by a multiplexer that sequences through the active channels, connecting them to the core that makes the measurements and digitalizes the sensor frequency. To measure the sensor frequency, the core uses a reference frequency (f_{REF}) which derivates from either the internal reference clock (oscillator), or a clock externally supplied. To support device configuration and to transmit the digitized frequency values to the host processor LDC1614 uses an I2C interface.

The reasons why the LDC1614 is the converter chosen rely on having multiple high-resolution channels, supporting remote sensing, performing with low cost, power and size, being a compact solution with a lower number of ICs needed, these features make this converter very useful for SHM applications. Other LDC1614's advantages with importance to this work are the precision dependence on the resonant driver circuit, the chosen capacitor and the oscillator. Being the last one the most critical, one can use external temperature compensated oscillators for better accuracy

E. Narrowband-IOT

The NB-IoT module consist in the Telit ME310G1 module to prepare the hardware of the device to report alarms previously deliberated directly to the cloud. This module permits the implementation of low cost IoT device, having a small size, and a low power consumption. ME310G1 is compliant to 3GPP Release 14 Cat M1/NB2, that enables increased power saving for IoT application using Power Saving Mode (PSM) and extended Discontinuous Reception (eDRX). This allows devices to wake up periodically, while delivering only the smallest quantity of data needed before returning to sleep mode. The improved coverage supports superior in building penetration when compared to previous cellular Long Term Evolution (LTE) standards. The devices with LTE Cat M1/NB2 are developed with small cost, size and power consumption. 3GPP Release 14 adds techniques to increase the data rate for LTE M and NB IoT.

F. Printed ciruit board

In order to achieve the goal of the project, it was designed a Printed Circuit Board (PCB). It is a 2-layer PCB board, with 50 x 100 mm, that includes the final system that fulfills the objective. The modules previously described are divided into sections in the PCB shown in Figure 4. The antennas needed to the Bluetooth (right) and for NB IoT (left) are place in the top of the board represented by the letter A. Going down in the board, in letter B there is the processor module with the ESP32 and the 26 MHz crystal oscillator. With the letter C is represented the footprint of the ME310G1 module not soldered because this module is not available until this date, and because of that all the components that support it are also not soldered. The letter D and E together make the power management module, being by the same order the switching regulator and the linear regulator. The peripherals zone is in the bottom part of the board. One of the two LDC1614 of the ECT module is placed in letter F, and in spite of there is a board hardware ready for read up to eight coils, in this project is just soldered one. To connect the probes to the LDC it is used a header that is represented by letter H. In letter G, the environment sensors module with the Si7021 and the LIS2D12 sensors are represented. A battery holder was welded in the bottom layer of the PCB to not interfere with the other components placed in the top layer.

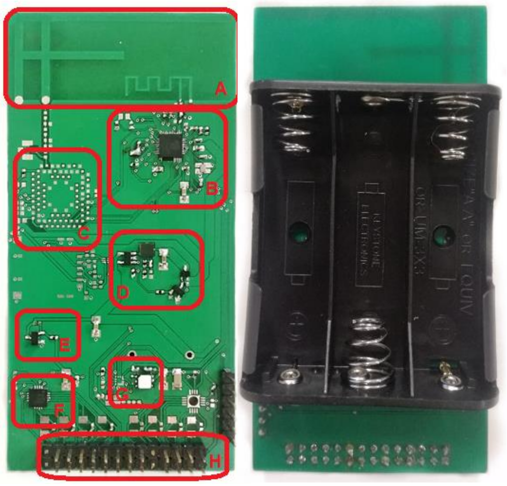

Figure 4 - Main Board PCB top layer (a) and bottom layer (b).

IV. Firmware and Software

In this section, the programming of the whole project is explained, which is divided into the serial protocol chosen to communicate between the peripherals and the device, and the communication protocol that was developed to achieve the purposed objectives and the GUI responsible to control the communication and present all the results of measurements.

A. Communication protocol

The device communication with the host is based on a communication protocol created in specific to this application to complete the purpose stated.

The protocol established allows bi-directional transmission of several elements is composed with commands and which command is divided in four variables of type unsigned integer in big endian format. Table 3 resumes the characteristics of each field of a command.

Table 3 - Commands description.

Command field	**Length**	**Definition**
Function	4	Defines the action or configuration to make or adjust
Value	4	Used when only a single parameter is required, and for example to identify a channel
Size	4	Zero if no more data is required or to specify how much additional bytes shall be received
Data	4 * Size	A variable size array with the remaining elements required to the function

Knowing the command structure, the device waits for the reception of the complete command header, that in this case are twelve bytes (four bytes for the function plus the value plus the size). It analyzes the size field and if the result is different of zero, the system receives an extra data with size equals to 4*size field on dynamically allocated memory. The slave application layer has the responsibility for interpreting the command struct and reply. The commands with the necessity of a reply, the slave unit has to reply with the respective data. In other way, an acknowledge command, with the same field function and value (equal to 1) will be replied. Three function named build_command, receive_cmd and send_cmd are created. The build_command function forms a command_t structure. To receive a command from the host it is created the void received_cmd function, that accesses to the first twelve bits and one by one put them in the command header, and if the size field is different than zero it puts the rest of the value in the data field. To send a command to the host side there is the void send_cmd function, which writes directly through a Bluetooth class function the first twelve bits, and then if the size item is different than zero send the data field.

To complete the whole system, there are seventeen commands defined in the program and they are divided into two types: acknowledge commands and general commands. The acknowledge commands includes the OK acknowledge, and the NOK acknowledge. In Table 4 there is two examples of commands definition, one with the size equal zero and other with size field different than zero.

Table 4 - Commands definition example.

Command name	**Function**	**Value**	**Size**	**Data**	**Direction**
Read humidity	0x21	1	0	NULL	Host to Device

Change frontend conversion time	0x65	Channel	4	RCOUNT	Host to Device

B. Peripherals readout

All peripherals communicate with the processor through the I^2C serial protocol.

After the read temperature and read humidity functions are invoked temperature and humidity is collected through Si7021 sensor, which the 7-bit base slave address of the sensor is 0x40. As soon as a relative humidity measurement has been made, the data resulted from this measurement need to be converted to percent relative humidity. This conversion can be made by

$$\%RH = \frac{125 * RH\_Code}{65536} - 6 \qquad (4.1)$$

where *%RH* is the measured relative humidity value in percent relative humidity, *RH_Code* is the 16-bit word returned by the Si7021. To convert the temperature data returned from the sensor into degrees Celsius (ºC) it can be used

$$Temp\left(°C\right) = \frac{175.72 * Temp\_Code}{65536} - 46.85\,, \qquad (4.2)$$

where *Temp(ºC)* is the measured temperature in *ºC*, and *Temp_Code* is the 16-bit word returned by the Si7021.

When calling the read acceleration function the acceleration of the device is collected by the LIS2DE12 sensor through I2C interface. The 6-bit base slave address is 001100xb, the least significant bit (LSb) is modified with SA0 pad. If the SA0 pad is connected to the voltage supply, LSb is ‘1’, in other way if SA0 pad is connected to ground, LSb is ‘0’. In this hardware the SA0 pad is connected to ground, therefore the 7-bit base slave address of the LIS2DE12 is 0x18. To launch the accelerometer sensor, it starts with the initialization of the I2C interface and then read the WHO_AM_I register. If the register returns 0x33, the data rate is set to 400 Hz, the three-axis reading is enabled, the full-scale is set to $\pm$2g, the interrupts in INT1 and INT2 pin are disabled and sets the FIFO to bypass mode. After this, the accelerometer collects the acceleration of each axis. The data acquired is then divided by 63 that is the divider associated to $\pm$2g range.

The final peripheral is the LDC1614 that communicates with the processor through an I2C interface. The LDC1614 can have two 7-bit base addresses depending on whether the ADDR pin is connected to ground or the same pin is connected to the voltage supply. If the ADDR pin is set low the 7-bit base address is 0x2A, however if the ADDR pin is set high the 7-bit base address is 0x2B. When configuring the LDC1614, the device will always confirm that it happens with no fault. However, if there is some problem in the configuration the device alerts about it. The reference clock can be an internal clock or an external clock. The internal clock is an internal limited accuracy oscillator with a typical frequency of 43 MHz, the external clock can be supplied by an external oscillator when better accuracy is required. To accomplishing it, the device needs to change the *REF_CLK_SRC* bit of the LDC1614 register. Then, it has four input deglitch filter bandwidths (1 MHz, 3.3 MHz, 10 MHz, 33 MHz) and it is recommended to select the lowest setting that exceeds the highest sensor oscillation frequency. To achieve it, the device has to change the *DEGLITCH* bit of the LDC1614 *MUX_CONFIG* register. Other specification to be set is the conversion time that can be done by programming the reference count. In general, a longer conversion time provides a higher resolution inductance measurement, being 0xFFFF required for full resolution. To accomplish it, the device has to change the LDC1614 *RCOUNTx* register. One more step is changing the conversion offset value, that is a value that may be subtracted from each DATA value to compensate for a frequency offset or maximize the dynamic range of the sample data. The device has to change the LDC1614 *OFFSETx* register. Then, the sensor activation time is the amount of settling time needed for the sensor oscillation amplitude to stabilize, and the settling wait time is programmable. To complete this configuration, the device has to change the LDC1614 *SETTLECOUNTx* register. There is also a need to change the channels reference clock divider, that has the *FIN_DIVIDER* and the *FREF_DIVIDERx*. To achieve it, the device needs to change the previous fields in LDC1614 *CLOCK_DIVIDERx* register. Other parameter is the drive current, and the *DRIVE_CURRENTx*. To finish the LDC1614 configuration there is an important command that is capable of reset the device. To achieve it, the device needs to write in LDC1614 *RESET* register that stop any active conversion and all registers return to their default values.

When the LDC1614 configuration is done, the next step is the collection of data of the probes connected to the LDC1614. To do this, the host can choose between show the outcome of one acquisition per channel or the continuous acquisition per channel. To present the measurement of the continuous acquisition, the host has a graphical application with a graphic per channel. To accomplishes the acquisition, the device needs to read the *DATA_MSB* register and the *DATA_LSB* register in this same order. After the collection of data, the device must send the measurement result to the host. The data received has to suffer one conversion from digital to the inductance International System of Unit (SI) that is the henry (H). to do this, first it is need to calculate de frequency sensor by

$$f_{sensor} = \frac{DATAx \times f_{REFx}}{2^{28}}\,, \qquad (4.3)$$

where f_{sensor} is the sensor frequency, *DATAx* is the digitalized sensor measurement for each channel and f_{REF} is the reference frequency for each sensor. After calculating f_{sensor} through (4.3), it has to calculate the inductance through

$$f_{sensor} = \frac{1}{2\pi\sqrt{LC}}\,, \qquad (4.4)$$

where f_{sensor} is the sensor frequency as previously denominated, *L* is the inductance in henry and *C* is the capacitor in parallel with the probe coil the probes in Farad.

The LDC1614 driver also includes the possibility of the device working in an autonomous mode, constituted by the store, load and automation functions. Starting with the store command, it stores the current configuration, defined by the host, permanently for later use on autonomous mode. For this, the device has a ldc_conf structure array with four positions, representing the four channels. The structure is saved in non-volatile memory. For the host to have access to the previously stored configuration, it has the load function that is able to read the ldc_conf structure variable, and to send it back to the host. To complete the automation, it is called the automation function that, with the access to the ldc_conf structure variable stored previously, perform the configuration of LDC1614 and the readout of the active channels. This function after configuring the LDC1614 active channels perform the readout of the channel for 10 seconds. The readout of the active channels is represented in four graphic items in the GUI. When there is a significant change in the readout value compared to the last value read, there is an alert message that appears in the interface indicating a fault identification. The significant change value is defined in a threshold value saved in the host side.

C. *Graphical User Interface*

This interface is developed in Spyder, in Python language. The first tab, named commands definition tab, is the one reserved to connect or disconnect with device through Bluetooth, to LDC1614 configuration and to read a single value from the probes. The Commands definition tab has a Connect button that after being pushed search for Bluetooth serial ports opened to connect and when a port is found the device is actually connected with the host. The Disconnect button disables the Bluetooth module of the ESP32. To program the LDC1614 with the respective commands the Program button is pressed and to reset the LDC1614 configuration the Reset button is the one. To collect a single value of one or more probes, it is needed to push the Read button. To choose which channels to program or read, it is required to enable the checkbox below the title.

The second tab, named data acquisition tab, presents the continuous reading of the four inductance sensors with the start and stop control buttons. In the tab there is a Start and Stop button. The Start button only can be pushed after choosing which probe or probes the user want to collect continuously data from. To stop this collection the Stop button is pressed and the checkbox became enable.

The third tab, named autonomous mode, is reserved to store the values presented in the first tab or to load to them the last values stored on the device, and to represent the values collected in the autonomous mode. The autonomous mode tab has three buttons. The Load button that calls the load function previously described, the Store button that runs the store function also previously explained and the Automation button that program the LDC1614 with the last configuration stored and collects for 10 seconds data from the channels defined active in the last configuration stored.

The fourth and final tab, named environment data tab, is where it is shown the environment sensors results. The environment data tab is the only one with one button. The Read environment button request the temperature, relative humidity and the acceleration of the three axes to device and presents the value in the spaces below.

D. *Main execution flow*

The main execution flow is in the flow chart diagram represented in Figure 5. Beginning, the device waits until 2 minutes for a Bluetooth connection. If there is no host ready to connect until time passes, the program goes directly to the autonomous mode. In case of there is a host ready to connect the connection is made, and the program continue in a controlled mode by the host. To control the device, the host sends a command that the devices, after receiving it, has to identify. If there is the automation command, the program jumps to the autonomous mode and perform the active channels readout. However, if the command is other, the device perform the function. If it is a configuration function, the device will send an OK message to the host, but if it is a reading measurements function, the device will send that results to the host. In both cases, the host can see and analyze the information received in a GUI.

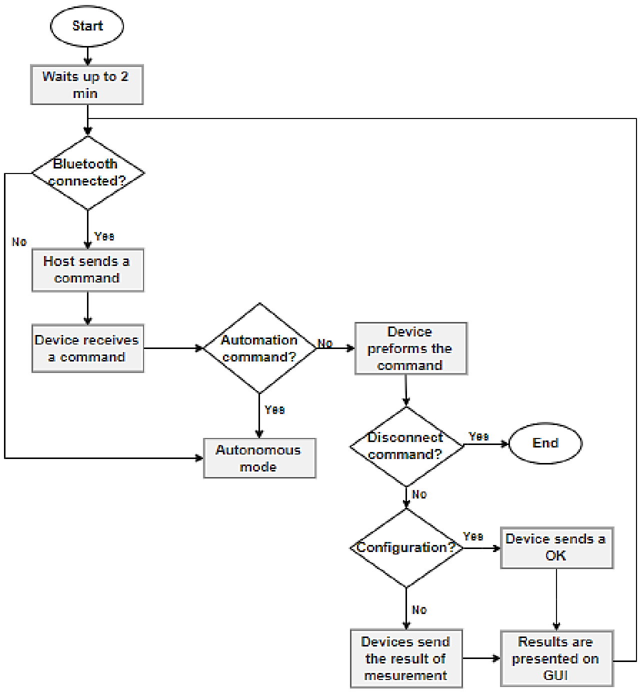

Figure 5 - Main execution flow chart.

V. SYSTEM DESCRIPTION AND MEASUREMENTS

The idea is to prove that the system works and the ECT is a good method to combine with SHM. To do this it was necessary to build a setup able to keep up the movement of the test structure and analyze the structure failures.

A. *Setup*

There is a need of a setup capable of following the metallic structure to test. This set up is in Figure 6. The letter A is the PCB designed with the system. The letter B is the probe used to read the inductance. The letter C represents the metallic test structure with the faults to identify. The principal perpendicular crack to be detected is represented by letter D and the longitudinal crack to be analyzed is in letter E.

To the system being able to be an ECT system, it needs to include an eddy current probe constituted by coils to detect the crack. As seen in Figure 6 with the letter B, the probe is a flexible circuit with 8 coils disposed horizontally, however only 4 are used to validate the system. The flexible circuit strip has a 16-pins header terminal to connect with the device, but only the eight central pins are connected to access to the four central coils of the flexible circuit. The flexible circuit probe has 12 cm of length and 1.3 cm of width, and the center of each coil is distanced 1.5 cm of each other.

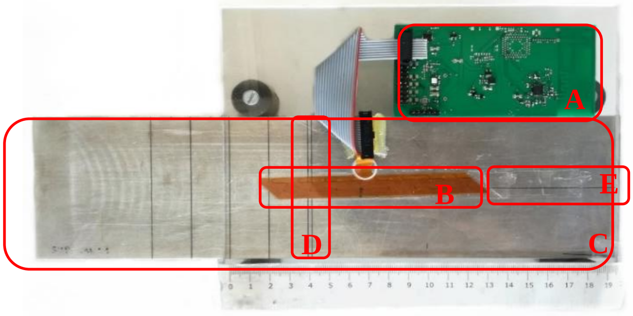

Figure 6 - ECT setup.

To discover the value of each coil, it was used the Hioki 3522-50 LCR HiTESTER, that is an LCR meter. The rounded value of each coil is 2 µH. Knowing this value and compared with the LDC1614EVM hardware and behavior, it is possible to calculate the value of the parallel capacitor. The value of the coils of LDC1614EVM is rounded to 8 µH and the value of the capacitor is 330 pF, so as the coil used has a value of 4.7 µH, the capacitor has to have a value of 3.3 nF, for circuit to resonate around the same frequencies. In Table 5, it is represented the value of each coil measured with the developed system, when the probe is over the metallic test structure and when it is in the air (without any conductive material under it).

Table 5 - Coils value.

Channel	Coil value in air (µH)	Coil value over conductive material (µH)
Channel 0	4,7176	1,8774
Channel 1	4,8058	1,8504
Channel 2	4,6608	1,7138
Channel 3	4,7571	1,8381

To start the evaluation of the system it is required a metallic test structure, which has 8 cm of width, 30 cm of length and 3.5 cm of height. In the side used to test, it has a crack every 2 cm. To the probe be able to follow the test material it is build an acrylic structure with 20 cm of length and 17 cm of width. To support this acrylic, it is screwed four supports with 3.5 cm of height. Glued in the bottom part of the acrylic is the probe. To be able to the host to has a better notion of distance, the acrylic has a scale.

B. *Data acquisition*

The configuration used to program the LDC1614 channels was the same in each of them. The reference clock used was the internal one with approximately 43.4 MHz, a deglitch of 3.3 MHz, a *RCOUNT* of 0xFFFF, an *OFFSET* of 0x0000, a *SETTLECOUNT* of 0x0400, a *CLOCK_DIVIDER* of 0x1001 and a *DRIVE_CURRENT* of 8C40.

In Figure 7, a set of measurement made over 6 cm, 2 in 2 mm is presented. The abscissa axis is the distance measured in millimeters and the ordinate axis is the data values in micro henry. The probes are in parallel with the test material, being the Channel 0 the first to detect the first crack. The first defect to detect was at 12 mm of the initial position of the setup. The maximum value reached by this channel was 2.1105 µH. Circled in red in Figure 7 is the first defect detection of each coil and the value that is measured is legend on top of that. One thing that can be detected is that each channel detects the first defect with a difference of 14 mm of distance. That is, the coils are distanced from each other the 14 mm of distance.

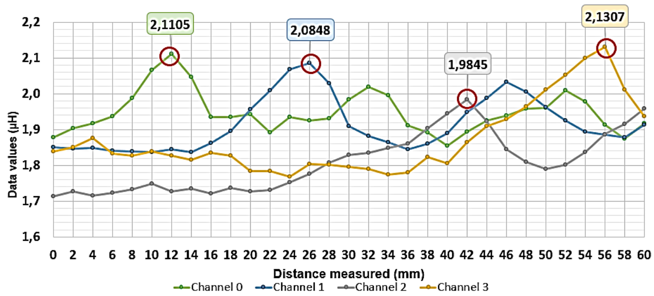

Figure 7 - Measurements over distance through four channels, perpendicular cracks.

In Figure 8, a single channel acquisition over distance is represented. The channel represented is the Channel 0. As it is visible in the Figure 8, in the distance of 6 cm the Channel 0 can detect three defects, circled in red. The first one is detected at a distance of 12 mm, the second one at a distance of 32 mm, and the final one is detected at 52 cm of distance. What can be taken of this image is that each detect is separated by 20 mm of distance.

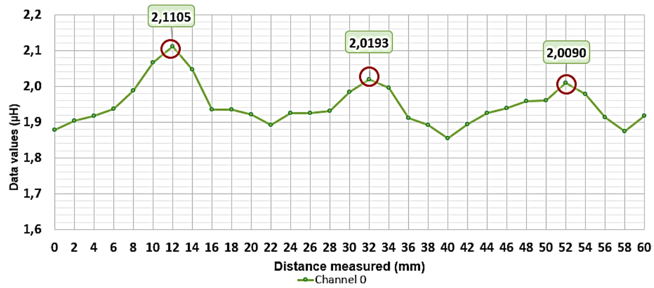

Figure 8 - Measurements over distance through Channel 0, perpendicular cracks.

In Figure 9, a set of measurements made over 6 cm, 2 in 2 mm is present. The crack in test now is the longitudinal crack, which means that the probe will follow the crack over distance. The Channel 0 is the first to detect the defect in the material. Highlighted in red in Figure 9, it is represented the distance at each coil detected the defect. Besides detecting the crack, this also shows that the defect is deeper as the distance from the original point increases. It can also measure the length of the defect, being more than 4.6 cm due to the fact that ate the final distance the inductance value of the first channel keeps increasing.

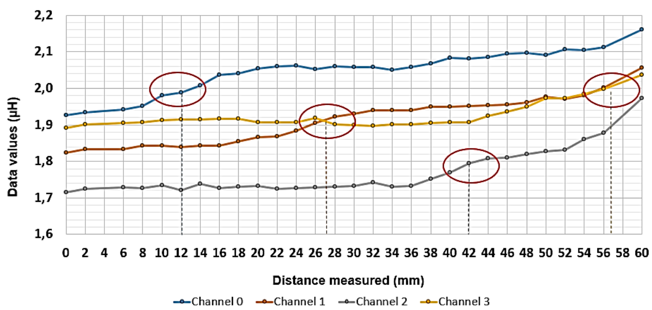

Figure 9 - Data acquisition over distance, longitudinal crack.

C. *Production cost*

After the development of the ECT system, it is time to prove that it is a low-cost circuit. In Table 6 is present the cost associated, with an estimative value for under than one hundred units. After analyzing the production cost of the final system, it can be proved that the system is a low-cost production.

Table 6 - Production cost.

Quantity	**Item**	**Unitary Price (€)**	**Price (€)**
1	Crystal of 26.00 MHz	0,927	0,927
1	ESP32	2,88	2,88
2	LDC1614	5,01	10,02
1	LIS2DE12	1,19	1,19
1	SI7021-A20	2,75	2,75
1	Others	10	10
1	Assembly	15	15
1	PCB	3	3
		Total:	45,767

VI. CONCLUSION

In this report it is proposed an IoT approach for SHM using eddy current probes to monitor a metallic structure in a real-time operation or in an autonomous operation, permanently.

To validate the implemented NDT method, it was elaborated a system composed by a set of four coils, but hardware ready for up eight coils, placed over the cracks previously identified, to determine the length of a failure that is aligned with the probe. The impedance generated by the coils is converted to digital by the LDC1614 for the rest of the system, and this information is accessed by the ESP32, through I^2C. To better evaluate the damage in the structure, a set of sensors to measure the environment where the structure is placed is an important tool, and that is why an accelerometer, a temperature sensor and a humidity sensor are necessary. Besides the system described there is the possibility of communicate with a host through Bluetooth protocol. A GUI is built to summarize the results, show them to the host, and also control the device.

Combining all this together, the achieved goals of implementing this device reside on demonstrate the benefits of using SHM systems to obtain better results in monitoring structures, and in particular metallic structures through the use of NDT specially ECT.

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