Integrating an Eddy Current Testing Structural Health Monitor

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***Abstract*—The use of Non-Destructive Testing techniques has seen a growth in use, in the last few decades. These techniques allow the monitoring of materials without damaging them and have been prominent in industrial settings. One of the domains of Non-Destructive Testing is Structural Health Monitoring, a field focussed in performing periodic measurements on the state of structures. This information can be used to observe the evolution of damage and define when maintenance teams should act on the damage. Eddy Current Testing is an electromagnetic method, with relevance in the Non-Destructive Testing field, used to inspect the state of metallic materials. This method can detect flaws through induction and sensing of electrical currents. The presented work begins with a continuation of the development of a battery powered device, capable of acquiring Eddy Current measurements, temperature and acceleration. A Graphical User Interface was also developed, which communicates with the device through Bluetooth and allows the configuration and viewing of the data acquired by said device. The device can also operate autonomously, performing measurements periodically and sending them through the Long-Term Evolution network. These measurements are sent to the Thingspeak cloud platform, where they can be analysed without the need for being in the device's vicinity. Relatively to the results, it was possible to confirm the device's capability of detecting a large crack in an aluminium plate, which is a good indicator of the utility of this concept with the objective of performing Structural Health Monitoring.**

***Index Terms*—Non-Destructive Testing, Structural Health Monitoring, Eddy Current Testing, Internet of Things, Digital Signal Processing.**

I. INTRODUCTION

NON-DESTRUCTIVE testing (NDT) refers to any technique used to test a product or material, without impairing any of its characteristics. It gained recognition and importance in recent times, due to the advances of technology, where structures of both high importance and risk were developed, such as nuclear power plants, aeroplanes and bridges. Combining NDT technologies with the aforementioned structures, ensures that regular checks are performed, thus increasing their safety, while decreasing the need for human intervention [1][2].

With access to modern technology, it is possible to perform tests that do not affect the characteristics of the materials, while obtaining data about the structure, that can be analysed and used to understand its state in critical points. With this information, failures as cracks and corrosion can be detected and repaired.

Structural Health Monitoring (SHM) is the process of monitoring the condition of engineering structures, with the goal of performing predictive maintenance and life extension of said structures. SHM informs the decision-makers of structural dangers, enabling a timely answer to abnormalities. This translates into the safer operation of the monitored structures, which, in the long run, should translate into cheaper costs (by preventing destructive events through targeted maintenance) and, possibly, avoid the loss of human lives. The technique relies on the periodic readout of pre-detected or failure-prone features of an ageing structure. Worldwide application examples include monitored structures such as bridges, towers, dams and oil platforms. From the multitude of NDT methods, Eddy Currents Testing (ECT) is a natural candidate for SHM integration due to the simplicity both concerning implementation and results readout [3][4].

Eddy Current Testing (ECT) refers to the use of electromagnetic induction, with the objective of acquiring information about conductive materials. This information can be analysed and interpreted in the context of finding flaws or cracks in surfaces, it is a useful method with decent versatility, which does not require hazardous substances, such as radiation [5].

This work aims at designing a connected SHM device implementing the crack detection or growth monitoring in a metallic structure by ECT means. The device will be based on a previously existing device that uses the ESP32 processor and an NB-IoT module, connected to an ECT electronics peripheral [6]. This peripheral will be integrated, by enabling the option of operating not only multiple channels, but also multiple chips (thus allowing the limit of 4 coils to be surpassed) and allowing a larger area to be analysed. Through the multi-channel acquisition, the option of referencing all channels to one will allow a better compensation of the environmental factors. The component of signal processing will also be important for the goal of detecting cracks. A cloud service and a web-based dashboard will be used for status and results reporting, allowing the scalability of this solution to multiple devices, providing remote access to the acquired data.

II. BACKGROUND

A. Non-Destructive Testing

Non-Destructive Testing refers to a series of techniques, used to determine the characteristics of materials, objects or structures and detect potentially critical defects that can affect their usability or integrity, without the occurrence of damage as a result of the testing process.

Ever since the beginning of times, Non-Destructive Testing has been performed using sensory tests, such as eyesight, hearing or touch. These rudimentary tests were able to evaluate structures and objects with low precision. The solution to prevent catastrophic failure of structures was to over-design, by requiring material in excess and including redundant supports. The few tests that were performed were mostly subjective, which would seldom lead to failure at later dates [1].

With modern technology, it became possible to perform tests with more objectivity, thus more precise conclusions can be obtained from the extracted data. History shows that NDT developments have usually been fuelled by economic, social and political pressure [7]. There are several different methods of NDT that can be used to analyse different materials and surfaces. These methods are highly dependent on various factors such as the type of material and its dimensions, the environment and the periodicity of data acquisition needed. A few examples of NDT methods are radiography, thermal imaging and eddy current testing.

B. Structural Health Monitoring

Structural Health Monitoring (SHM) refers to the process of continuously monitoring the conditions of a structure and its components, with the objective of providing a clear and objective evaluation of said structure's state. To do so, it employs non-destructive testing to obtain objective data. This is done through the integration of sensors, which collect data, this data can be analysed in order to detect flaws and defects in the structure. By performing regular measurements and storing their history in a database, SHM enables the use of the data to form a prognosis, which can be used to observe the evolution of damage.

The real-time knowledge of the structure's state allows the maintenance teams to perform more precise and focused intervention, thus minimizing the downtime, while avoiding catastrophic failures. The general maintenance workflow is also overhauled, replacing periodic maintenance with performance-based maintenance and reducing the need for human intervention, which consequently reduces the occurrence of human errors.

Safety is one of the big concerns that brings SHM to light, however, to the end-user, the economic gains seem to outweigh the safety ones. With the introduction of SHM, the maintenance costs are reduced, while providings greater reliability, in contrast to the increasing maintenance costs and decreasing reliability for structures that do not implement these monitoring methods [3].

C. Eddy Currents Testing

Eddy currents testing (ECT) refers to the use of eddy currents in order to detect flaws in conductive materials. Eddy currents are currents that are induced in conductors by a changing magnetic field. These currents flow in closed loops close to the surface of the conductor. When this magnetic field is created by a coil, the resulting eddy currents can change the current in the coil, due to the effect of mutual induction. These changes in the coil can then be measured, providing information about the conductor analysed and, thus, allowing ECT to be performed.

In the current times, ECT is a widely used method of SHM. Due to the development of low-power microprocessors in recent decades, the implementation of battery-powered devices attached to eddy currents sensors became possible. These devices are crucial in the SHM field and are used in many industries.

The physics behind EC can be explained by the laws of Ampere (Equation 1) and Faraday (Equation 3). According to Ampere's law, the integral around a closed path S of the component of magnetic field tangent to the direction of path is

$$\oint_S \overrightarrow{B}.d\overrightarrow{S} = \mu I, \tag{1}$$

where μ is permeability of the material and I is the electrical current flowing through the surface of material enclosed by the path S. Assuming that the wire is long, the value of the magnetic field B can be calculated with

$$B = \frac{\mu I}{2\pi r}, \tag{2}$$

where r is the distance to the wire, assuming a perpendicular direction to the flow of the current.

According to Faraday's law, the electromotive force (also known as EMF) is equal to the rate of change of magnetic flux, as seen in

$$\epsilon = -\frac{d\Phi_B}{dt}, \tag{3}$$

where the magnetic flux Φ_B is given by

$$\Phi_B = \int \overrightarrow{B}.d\overrightarrow{A} \tag{4}$$

where $\overrightarrow{B}$ is the magnetic field and it is integrated in order to account for the presence of it along the area of the surface $\overrightarrow{A}$.

In practice, when a coil is subjected to an alternating current it generates an alternating magnetic field. When near a conductive surface, it generates the electrical currents in said surface (the eddy currents). These eddy currents are usually concentric, however, in the presence of defects or other irregularities, their path is modified. In turn, these eddy currents generate a magnetic field, which interacts with the one generated by the coil. By measuring the characteristics of the coil, it is possible to find defects and irregularities. In Figure 1 a representation of this process can be found.

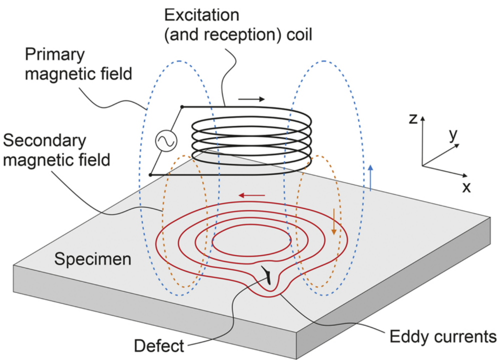

Fig. 1. Illustration of ECT with a distorted eddy current flow due to a defect in the test specimen [8]

III. IMPLEMENTATION

A. *Overview of the system*

The main objective of the proposed system is to acquire eddy current measurements, over a period of time, and communicate the result of these measurements onto a platform where the data can be interpreted. The interpretation of the data should allow to monitor the health of the structure and to make the call to take further inspection of a certain area in case of abnormal readings.

In order to standardise and simplify the process of configuration of each device, a graphical user interface was developed. It acts as a local interface, which communicates with the device and allows the modification of settings relative to the configuration of the sensors, the frequency of measurements and the periodicity the data is uploaded to the cloud. Its main objective is to serve as an option to install the sensor.

The selected cloud platform is the Thingspeak, an open-source IoT platform focussed on IoT sensor systems. Through this cloud it will be possible to observe the measurements and also check for the existence of alarms, which warn about the existence of a possible crack or abnormal deformation of the monitored structure. The diagram of the full system is represented in Figure 2.

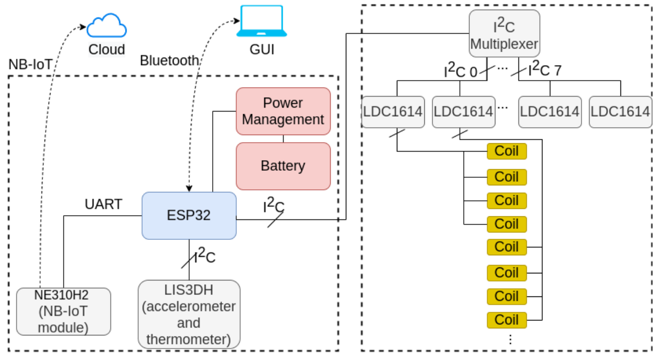

Fig. 2. Diagram of the full system.

The I^{2}C multiplexer is capable of connecting to a maximum of 16 LDC1614 sensors, by having 8 different I^{2}C outputs, which in turn, each of the outputs is connected to two LDC1614 sensors, differentiated by their address. This means that with this configuration it would be possible to have a maximum of 64 coils, distributed through the 16 LDC1614 sensors.

The system that acquires the data itself is centred around the ESP32 microcontroller. It can be seen in Figure 3, where several components (such as the ESP32 and the NE310H2) are mounted onto.

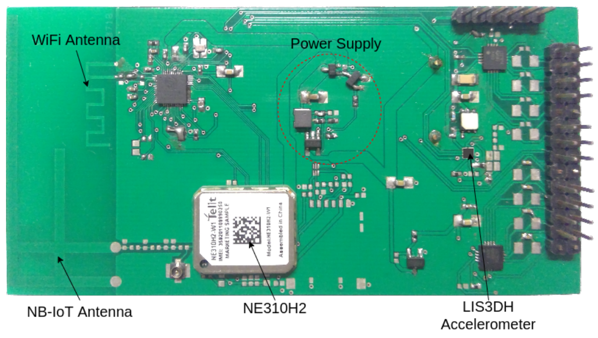

Fig. 3. PCB with the ESP32 microcontroller used to control measurements.

The hardware for the eddy current measurements is located on a different PCB which is attached to the main device via DB9 connectors. A battery holder for 3 AA batteries, attached to the opposite side of the PCB is shown in Figure 3.

Fig. 4. Bottom side of the PCB.

A top view from the PCB with the hardware to perform the eddy current measurements can be seen in Figure 5. The 4 similar-sized black chips are LDC1614s, each of these chips is then connected to 4 coils. This means that in this configuration there is a total of 16 different coils. The connection between the reader and the probe is modular. With this connection, it is possible to use probes with different geometries.

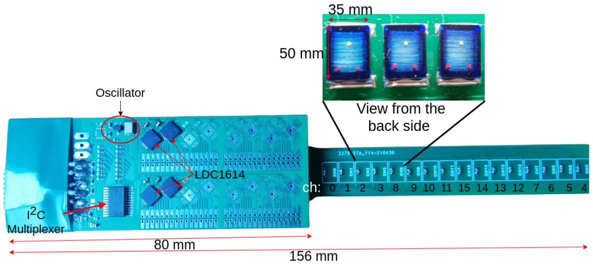

Fig. 5. Top view of the PCB which performs resonant measurements.

B. Flowchart of the ESP32 logic

The flowchart of the ESP32 logic is laid out in Figure 6. The Bluetooth intricacies are hidden in this representation.

In short, the logic of the ESP32 flowchart is divided into 2 branches, one where the ESP32 is booted for the first time and the other, where it wakes up after having performed deep sleep. In the first case, it awaits for a possible incoming Bluetooth connection, coming from a user of the graphical user interface. In the latter, the device is already working in autonomous mode and the fact that it woke up means that the device is supposed to acquire measures at that time. In turn, the branch where the device wakes up after deep sleep is also divided into 2 branches. It always performs the resonance measurements, however the data is only uploaded into the Thingspeak cloud when a certain number of files has been reached. This number of files corresponds to the number of times the device woke up after having successfully uploaded the data, the last time.

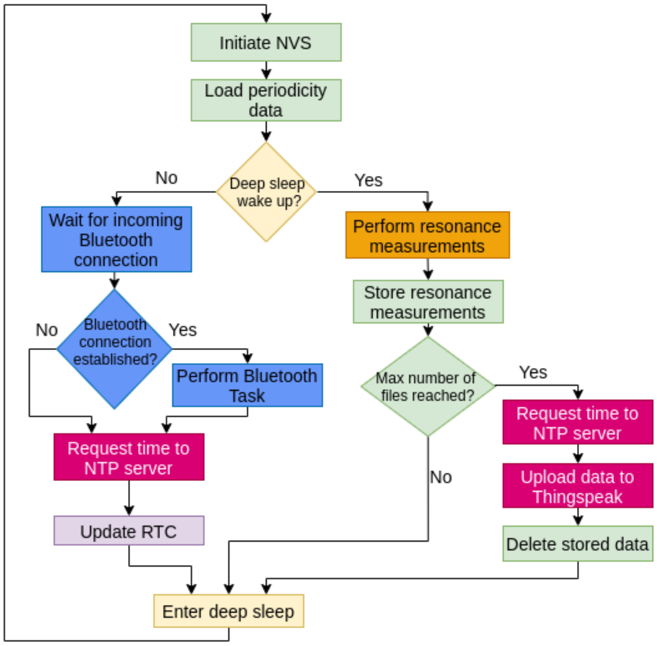

Fig. 6. Flowchart of the ESP32 runtime logic.

C. LDC1614

The LDC1614 is a low-power, low-cost and compact inductance to digital converter, capable of a wide range of inductance and oscillation frequencies. Considering the existence of multiple LDC1614 modules, when powering one on, the address used by I^2C must be updated according to the selected LDC1614 chip.

The measured values are acquired by counting the number of oscillation cycles in a known and configurable time base. These values are read from two 16 bit registers and the 4 most significant bits are discarded, meaning that the measured values have a 28 bit resolution. After being read, the value must then be converted into inductance. The conversion is performed by firstly applying Equation 5, where the frequency of the sensor is calculated.

$$f_{sensor} = data * \frac{f_{ref}}{ratio\_factor}, \tag{5}$$

where f_{ref} is the configured reference frequency, $ratio\_factor$ is the ratio of the sensor frequency to the reference frequency and data is the value read from the data registers. After retrieving f_{sensor}, plugging it in Equation 6 will yield the inductance of the measurement that was read.

$$L = \frac{1}{(2 * \pi * f_{sensor})^2 * C}, \tag{6}$$

where L is the measured sensor inductance, f_{sensor} is the sensor oscillation frequency and C is the nominal capacitance of the capacitor used.

In order to minimize the amount of data transferred, while maintaining the reliability of the data, the system acquires several measures in the same channel in a short succession of time. This data is then converted to inductance through Equation 5 and Equation 6, which is then calculated into a mean and a variance of the total amount of measurements taken. The use of the mean and variance allows a reduction in the influence of noise and potential interferences and, thus, data easier to analyse.

D. Autonomous Mode

After the device initiates and ends a Bluetooth connection with the GUI or the time allocated for an incoming connection expires, it automatically initiates its autonomous mode. The autonomous mode's goal is to perform measurements, process them and send them to the cloud platform.

During this mode, the device is programmed to acquire measurements periodically, doing so by deep sleeping a configurable amount of time and performing said measurements when the device wakes up from deep sleep. The device does not send the measurements to the cloud platform every time it wakes up, it saves them in non-volatile storage, which assures the integrity of the data during deep sleep or power down. This is done to minimize energy consumption, by minimizing the number of times that data is sent to the cloud platform, and therefore the number of times the NE310H2 is turned on and activated for communications. The number of measurements stored until the device initiates the transfer onto the cloud platform is configurable and the periodicity of measurements (the amount of time that is spent during each deep sleep cycle) is configurable as well.

Each of the measurements is labelled by a timestamp, this timestamp is retrieved from the RTC clock, which is initially synchronized when the device is turned on. This clock does suffer from deviations, which means that after a long period of runtime, this deviation would be noticeable. To avoid unwanted time synchronization problems, when the device turns the NE310H2 module on, to send the measurements to the Thingspeak cloud platform, it also resynchronizes the RTC with a network provided reference timestamp, making sure that the time in the RTC is reasonably accurate.

E. Graphical User Interface

The GUI (Graphical User Interface) is a program meant to interface with the ESP32 device wirelessly, through Bluetooth. The GUI was programmed in Python 3 and in order to create the interface, the Qt 5 widget toolkit was used. Qt 5 is optimal for cross-platform applications, since it allows the compatibility with few changes to the code while remaining quick and efficient.

It has an initial window, which moves to the main one after the connect button is pushed and the connection is successfully established. The main window is divided into 4 tabs, each with its own functionality:

- In tab 1, the retrieval and insertion for parameters of each of the coils in the LDC1614's can be performed
- In tab 2, a real-time acquisition and viewing of the data acquired from every coil
- In tab 3, one can read and program the parameters relative to the autonomous mode (sleep time, max file num)
- In tab 4, it is possible to read the environment information (acceleration and temperature)

F. Thingspeak

Thingspeak is an open-source IoT application used to store data from diverse types of IoT applications. The data can be uploaded to it with both HTTP and MQTT protocols. Thingspeak is integrated with MATLAB, which enables this platform to offload processing from the uploading nodes (which are usually low power devices). With said MATLAB integration, it can also process the data, create graphical displays and generate alerts.

Since MQTT does not support bulk-write updates, the protocol chosen to communicate between the device and Thingspeak was HTTP. For small inputs of data into Thingspeak, the GET method may be used to send data into the platform. However, in order to limit the amount of time that the NE310H2 module (responsible for the NB-IoT communications) is powered on, the messages must send the data in bulk. To do so, the POST method is used to enable the bulk-write JSON data. With this, it is possible to send the data, acquired throughout the day, to the Thingspeak platform. For each coil, Thingspeak will have two different sets of data, one being the average of the acquired resonance measurements and the other one the variance of said measurements.

IV. RESULTS

A. Experiment Setup and Characterisation

The configurations, seen in Table I, are similar for all channels and are optimized for the data acquisition precision and rates needed for the intended application. These were the configurations that were used in the experiments that follow.

TABLE I
CONFIGURATIONS OF THE LDC1614 MODULE FOR THE EXPERIMENTS PERFORMED.

Attribute	Value
Reference Clock	EXT
Input Deglitch	3.3 MHz
Conversion Time	0x04D6
Conversion Offset	0x000A
Reference Clock Divider	0x2002
Drive Current	0xF000

In order to verify the precision of the LDC1614, the EC measurements performed with a single channel, during 1 hour, on a metallic surface. During this period of time, the temperature, registered by the LIS3DH accelerometer, was stable at 21 °C. This minimizes the influence of the effect of the temperature in the measurements performed. In Figure 7 it is possible to observe the distribution of the measurements during the test that was performed.

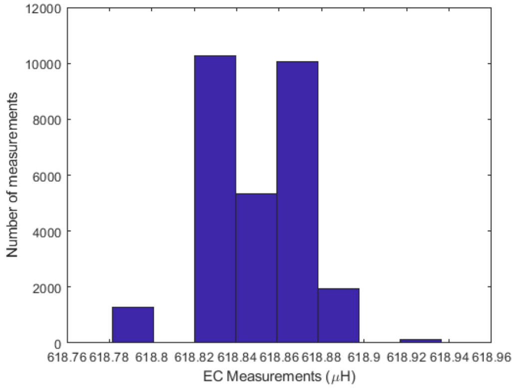

Fig. 7. Distribution of the EC measurements, with no variation of temperature.

The mean extracted from the data of this experiment was $618.848\,\mu H$ with a standard deviation of $0.022\,\mu H$. Considering that in this specific experiment there was an effort to minimize the changes in the external factors, the variation in measures observed is not ideal. One of the reasons for it, might be explained by small variations of temperature, which were not captured by the temperature sensor, due to it having a very limited resolution. The reference clock might have also influenced some of these variations.

B. Influence of Temperature

An experiment acquiring measurements on a metallic surface subject to external conditions, during a 24 hour period, was also performed. This experiment intended to demonstrate how the values of the measurements change throughout the day since the device is intended to be used in exterior conditions and external factors have influence in the EC measurements.

In Figure 8 it is possible to observe the EC values relative to a single channel (channel 0) while comparing the changes of the measurements with the variation of temperature. The resolution of the LDC, considering the configurations used, is (for values close to 619 μH) 0.4 nH/bit. During this experiment there were no position changes relative to the device, nor was damage performed to the tested surface.

It can be easily perceived that the variation of the temperature throughout the day, has a clear relation with the EC measurements values. During this period the temperature varied between 17 °C and 25 °C and it is visible that the curve of the EC measurements follows the temperature curve, peaking where the other peaks and bottoming when the other one bottoms.

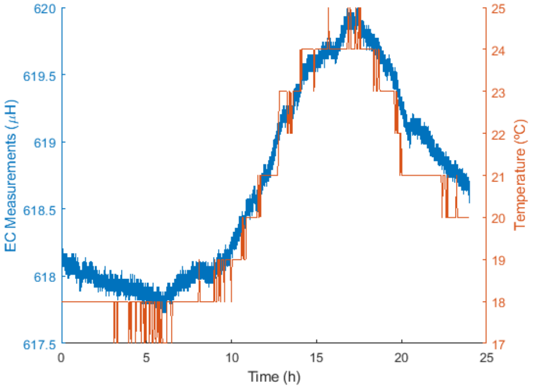

Fig. 8. EC measurements and temperature values during a 24h period.

C. Multi-channel Operation

As previously stated, each LDC1614 can only be connected to 4 coils. In order to explore the usage of several channels in a single probe, 4 LDC1614s were installed in the measuring board, which allows both the possibility of measuring a wider area, as well as the possibility of comparing measurements between channels. On the other hand, the usage of multiple LDC1614s introduces another variable that can provoke differences in measures between channels. In order to verify if the addition of more LDCs was actually a noticeable factor in the values of the measurements, two different plots were created.

The measurements acquired by channels in the same LDC are displayed in Figure 9, with the objective of finding if there are considerable discrepancies between these channels.

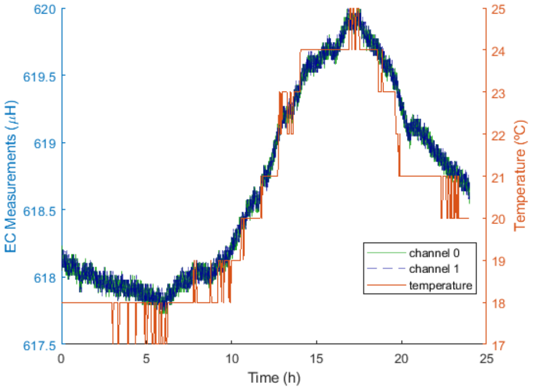

Fig. 9. Measurements of channels belonging to the same LDC1614 instance.

The measurements of the channels connected to the same LDC, output identical values consistently, as can be seen in Figure 9. This is a desirable characteristic since variations between channels should automatically mean that there was some form of change in the tested material, near the coil corresponding to said channel. Although not displayed here, it was verified that the previous observation remained true for the other LDCs as well.

The first channel out of each LDC instance is plotted in Figure 10, in an effort to expose the unmatch between different LDC instances. The data used for this experiment was the same as in the previous one, with the objective of providing a more direct comparison between them.

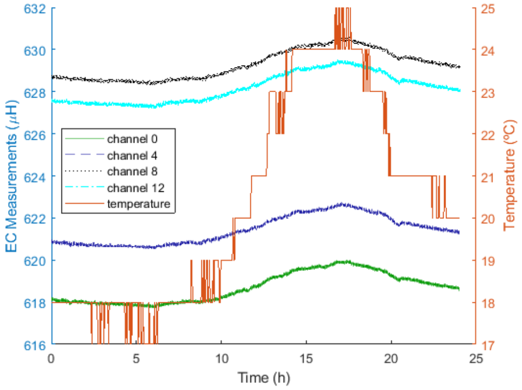

Fig. 10. Measurements of channels belonging to different LDC1614s.

Through the analysis of Figure 10 the differences between the channels displayed are obvious. Unlike what was observed in Figure 9, this time, the values corresponding to each channel have significant discrepancies. Although this is not ideal, it is also possible to observe that the discrepancies between the channels are relatively constant, that is, each curve follows the same pattern, meaning that referencing all channels to one should result in a roughly constant plot, when no damage is verified.

The offset of the curves for each of the channels, which belongs to a different LDC can be explained by many factors, namely: differences between the LDC instances, the fact that due to the layout of the board, the distance between the coils and LDCs is never the same and the tolerances of the coils and the parallel capacitors can also contribute to these differences.

D. Measuring the damage

The next step, was to analyse the variation of the measured values, when testing a surface with a synthetically added defect. To do so, an aluminium plate, which, at 20 °C, has a conductivity of $3.77 * 10^7$ S/m, was surveyed with the measuring device and the data from this experiment was studied. The setup used to measure the damaged surface is displayed in Figure 11. The measurement process started in the non-damaged part of the surface and was gradually moved in the direction of the flaw, until all coils were over it. The plate used has a thickness of 7 mm and the crack, which starts at the 12 mm mark, has a width of 3 mm and grows, from one side of the plate until the other side, at an angle of about 61.7 °.

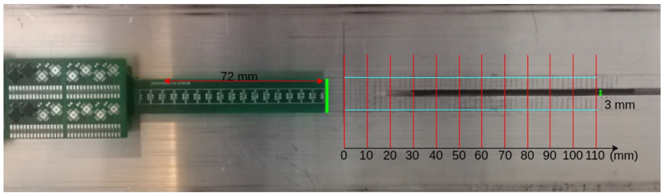

Fig. 11. Setup used to perform the measurements with a crack in an aluminium plate.

The idea behind this experiment was to emulate a crack, growing through the sensor. Since access to a mechanical system, capable of creating fatigue cracks, this was replicated by measuring a previously created crack and performing measurements while moving the sensor through the crack.

The position of the measuring board refers to the location of the edge of the measuring board (represented by the green line) relative to the referential shown in Figure 11.

The measurements performed in the previously described experience, where the measuring board moves in the same direction as the line created by the flaw, are represented in Figure 12.

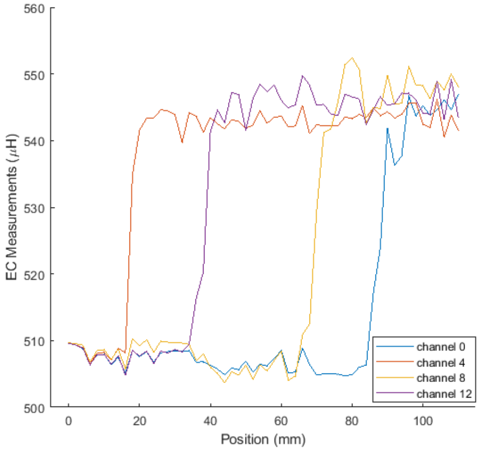

Fig. 12. Measurements of the damaged surface.

The measurements of the eddy currents, shown in Figure 12, are represented in μH. Taking into consideration that the bottom axis refers to the position of the measuring board, it is possible to observe that different channels sense the flaw at different positions. The flaw can be observed where the step in inductance occurs, i.e. in channel 8 when the board reaches the 20 mm position. As expected, the flaw is detected at different positions, depending on the channel and its relative position to the measuring board, which can be seen in Figure 5. Once again, the measured inductance between channels belonging to different LDCs is different, even when positioned over the same part of the metal board. As observed here, the presence of a flaw, in a non-magnetic material, reduces the eddy currents density, which increases the magnetic field of the coil and, in turn, the inductance.

V. CONCLUSION

The use of ECT allied to IoT has a big potential in the field of SHM, more specifically in the monitoring of metallic structures. Allowing the use of these technologies in this area can be beneficial not only in the field of safety but also economically viable. Installing EC sensors in critical places can provide regular insights into the state of the structure, without the typical costs required to deploy specialized teams. In this thesis, a device capable of performing automated eddy current measurements, with long term deployment capability and autonomous operation is proposed. This device is also capable of transferring data to a cloud platform, allowing the relevant data, which can be used to evaluate the state of the structures, to be observed without the need for close proximity to the device.

A GUI capable of communicating with the device through Bluetooth was also developed. This GUI allows the possibility of both configuring and performing debugging on the device, without the need for a physical connection. Its main goal is to provide an easy way to configure the EC sensor, adjusting it to the most suitable settings, according to the material being inspected.

The cloud platform used was Thingspeak, a platform created for IoT solutions with Matlab integration. The device uploads data into this cloud through NB-IoT, and the cloud stores the data and can implement algorithms to decide from the data if there are deformations in the material.

Through the acquired results it is possible to confirm that there is a correlation between temperature and the values measured by the EC sensor, meaning that these can be compensated. In order to eliminate the influence of the external factors, referencing all channels to one was carried to explore ratiometrics, since the coils are in close proximity to one another and should, thus, suffer roughly the same external factors. An experiment measuring the influence of damage in the testing material was also performed. By analysing an aluminium plate, the changes in the measurements of EC values were observed. The difference between measurements of the damaged section and the undamaged one was significant, proving, once again, that this concept is useful for structural health monitoring.

All in all, the results achieved in this thesis demonstrate that the concept of using a low-power and low-cost device for SHM is valid. A GUI for configuring the device was successfully developed, enabling a customized selection of parameters for both the parameters of the EC sensors, as well as allowing the visualization of the measured data in real-time. The transmission of data through NB-IoT to the Thingspeak platform was also successfully implemented, opening up the possibility of testing this device in a scenario similar to the one intended for its final use. Regarding future work, these are the topics that can be worked on:

- The use of artificial intelligence or algorithms to identify cracking patterns across the structure and predict failures.
- The setup of the LDC1614s and the coils can also be improved, in a push to increase the quality and reliability of the acquired data.

- The use of components, such as the capacitors and the shared clock, which are more resistant to temperature changes, thus, offsetting the influence of temperature in the eddy current measurements.
- In a more advanced stage, the implementation of this system in a large scale is an important step in the evolution of this project. This mass implementation would allow a reduction in cost per device (due to mass production) and the opportunity to test a wide variety of scenarios.

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