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Measurement Setup for the Development of Pre-Corroded Sensors for Metal Artwork Monitoring

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Abstract – **The monitoring on cultural heritage is key task for the conservation of masterpieces. When work of art made of metal are considered, this task can be performed by means of samples of material that play the role of corrosion sensor. In this work, a measurement system for the development and testing of sensor for metal corrosion evaluation is presented. The metrological features of the measurement system are analyzed aimed to the optimal analysis of a developed corrosion sensor. The sensor allows to consider also the effect of the masterpiece pre-corrosion so as to achieve a better evaluation of the actual corrosion process affecting the work of art.**

I. INTRODUCTION

The real-time monitoring of cultural heritage is a very important task for the proper preservation of works of art. Among them, metallic made ones are strongly affected by environmental corrosion that can irreparably damage their surface. The monitoring of parameters such as humidity, temperature, pollutants etc. is the easiest used approach that allows to control and reduce the metal degradation [1], [2]. More effective method requires to expose to the same environmental conditions the masterpiece to monitor and a sample made with the same metal. This approach allows to perform also invasive measurement on the specimen without damaging the work of art [3]. The most part of the sensor based on this approach do not take into account the effect of the surface corrosion state. In fact, it is well known that the presence of layers of results of the corrosion can modify the corrosion process [4].

In order to implement a more effective monitor of the degradation effect, pre-corroded sensors have to be developed and optimized. In a preliminary work, the authors have developed a sensor that can be preliminary corroded so as to emulate the actual state of the masterpiece to be monitored [5]. The sensor is based on printed circuit board (PCB) technology and it requires a measurement system performing an electrical resistance tracking over the time. The optimization of the sensor and corrosion process require a vast laboratory activity supported by high accuracy measurements and controlled environment.

In this paper the developed measurement system and its metrological characterization will be presented. The system has been thought in order to guarantee high measurement performances, flexibility, modularity, good number of acquisition channel and easy use. The metrological characterization allowed to optimize the measurement system parameters so as to achieve the best performance.

In the final paper the complete characterization including the effectiveness of the temperature compensation of the sensor thermal drift will be reported. Moreover, some tests on pre-corroded sensors will be provided as well.

II. SENSOR DEVELOPEMENT

The development of the sensor has been driven by needs concerning cost, flexibility, exposition surface area, measurement system characteristics and sensitivity. In particular, the developed sensor had to guarantee:

- good surface area to be attacked by corrosion agents,
- a proper distance between traces so as to avoid the presence of short circuit bridges due to corrosion results,
- possibility to be reconfigured by changing the sensor resistance value,
- allowing to perform a temperature compensation of the resistance variation due to temperature drift,
- low cost of production.

On the base of these constraints, a PCB solution has been adopted. The sensor has been designed in four sections, two for each face of the PCB to test different corrosion rates and implementing a temperature compensation as shown in Fig. 1. In this work terminal E and E' have been connected in order to consider a full PCB face exposed to corrosion.one face will be protected from corrosion and will be adopted as reference for the temperature compensation (R_R), while the other face is subject to corrosion (R_C).

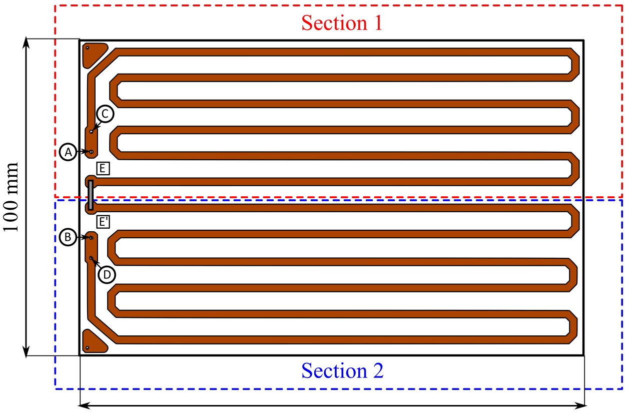

Fig. 1. Sensor layout.

In the preliminary design phase, different corrosion rates have been considered as listed in Table 1.

Table 1: corrosion rates.

	Highest	High Outdoor	High	Medium Outdoor	Low Indoor	Lowest
v_C [m/y]	$1\ 10^{-3}$	$1\ 10^{-4}$	$1\ 10^{-6}$	$1\ 10^{-7}$	$1\ 10^{-8}$	$5\ 10^{-9}$

The corrosion rate assumes ideally that the erosion of the material is uniform. This means that only the thickness of the sensor is ideally involved in the erosion process. Now, let us considering the expression of the resistance in terms of resistivity ρ and geometrical parameters:

$$R = \rho \frac{L}{S} = \rho \frac{L}{h\delta} \tag{1}$$

where, L, h, δ are respectively the total length, the width and the thickness of the PCB tracks. Therefore, there is an inversely proportional relation between the resistance of the sensor and the corrosion rate. Moreover, the choice of thickness leads the life of the sensors. The design of the sensor has been optimized in terms of lifetime and sensitivity for a specified level of corrosion rate, within a reasonable range of variation.

Measuring R_R and R_C, it is possible to compensate the thermal drift of the resistance by computing the ratio between the two faces of the sensor resistances for a generic temperature T:

$$K_C = \frac{R_C}{R_R} = \frac{R_{C0}\left(1+\alpha\left(T-T_0\right)\right)}{R_{R0}\left(1+\alpha\left(T-T_0\right)\right)} = \frac{R_{C0}}{R_{R0}} \tag{2}$$

where R_{C0} and R_{R0} are the corrosion and reference resistances at the temperature T_0 while α is the thermal coefficient of the conductive material of the PCB tracks.

In this way, monitoring the value of the ratio K_C it possible to quantify the corrosion effect. Naturally, the minimum detectable variation of K_C strongly depends on the resolution of the chosen instrument adopted to perform the resistance measurements.

After these considerations the geometrical parameters have been chosen as can be seen in Fig. 1. Tracks have been realized in copper with a thickness of 17 µm so that each face of the sensor has a nominal value of 0.317 Ω.

III. MEASUREMENT SETUP

In order to properly characterize the proposed sensor a VI-based measurement system has been developed (Fig. 2). The measurement setup has to guarantee good measurement performances, flexibility, modularity, good number of acquisition channel and easy use.

A Keithley 3706 has been used for performing the required 4-wires resistance measurements. In this way, no contact resistances are included in the resistance measurement. This instrument has been chosen as it provides multi-channel measurement solution by means of switching cards. In this way, different pre-corroded sensors can be tested with the same high resolution digital multi-meter (DMM) with an effectiveness cost solution. In fact, each switching card has 40 channels. The Keithley 3706 own four slots, so that potentially 160 channels can be acquired with one DMM. In this work only one switching card has been connected.

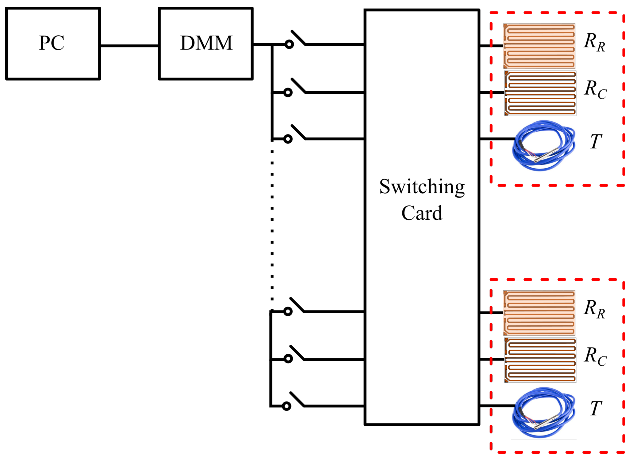

Fig. 2. Measurement system architecture.

For each tested sensor, three resistance measures are required: the resistance of the track exposed to corrosion, the resistance of the track used as reference for the temperature compensation and the resistance of the pt100 temperature sensor. Given this requirement, the measuring system is able to accommodate 13 sensors for their characterization.

Every single measure is the results of 50 averaged measures performed over 5PLC. The minimum analysis time for each sensor is 5s. These limits and configuration parameters have been defined on the base of a measuring system characterization that is reported in the following section.

For each measure the mean value and the standard deviation is measured and saved on a log file. The interface of the developed measuring system is reported in Fig. 3. The interface is made up of a configuration panel allowing setting the instrument parameters and a measurement panel on which the measurements over time of the three resistances are shown.

Fig. 3.VI front panel.

IV. MEASUREMENT SYSTEM CHARACTERIZATION

In order to evaluate the accuracy and the sensitivity of the measurement system a series of test have been performed. First, the measurement noise of the system has been evaluated by performing a measurement campaign on a standard resistance R_S=0.1 Ω characterized by low thermal coefficient and placed into a climatic chamber guaranteeing a temperature of 23.0 °C ±0.2 °C. The temperature has been monitored by means of a digital thermometer Dostman Elettronics modell P655-LOG with Pt100 sensor. In the meanwhile, a second channel has been used for measuring the resistance of one face of the developed sensor placed in the same climatic chamber. Referring to Fig. 1, the current was injected from terminal A and collected at terminal B while the voltage drop was measured between terminals C and D. This allows to evaluate the noise related to the sensor geometry and connections. The experimental setup has been reported in Fig. 4.

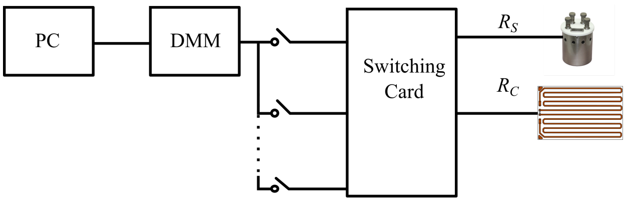

Fig. 4. Measurement system characterization setup.

The DMM range has been set to 1 Ω, suitable for both the standard resistance and the developed sensor. Dry circuit and offset compensation features have been enabled. The DMM in 4-wire resistance configuration allows setting the measurement time in terms of Number of Power Line Cycle (NPLC).

Moreover, the time between the closing operation between the switching card and the DMM can be controlled; this intentional delay time T_D can be used to ensure that the resistance measurements are performed when the system is in steady state condition.

In order to optimize the DMM parameters, different tests have been performed on the standard and the sensor resistances. N=100 measurements for both channels have been performed ranging T_D from 0 to 10 s and considering NPLC equal to 1, 5, 10. For each channel acquired in each test condition, the measurement noise has been estimated as the sample variance over the N measurement:

$$s_R = \sqrt{\frac{1}{N-1}\sum_{n=1}^{N}\left|R^{[n]} - R_{\text{avg}}\right|^2} \qquad (3)$$

The standard deviation has been performed for both the standard resistance R_S and the sensor resistance R_C on the N measurements. Results have been reported in Fig. 5 and Fig. 6 respectively for different T_D and NPLC.

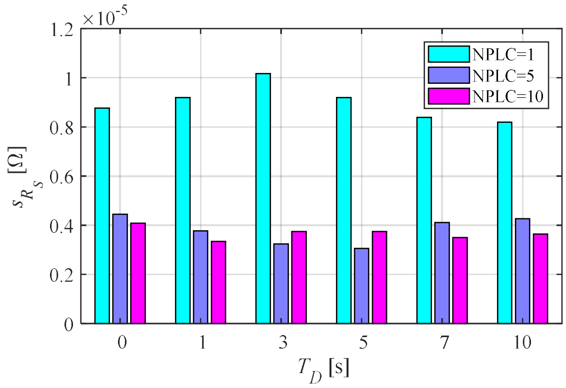

Fig. 5.Standard deviation of R_S in different test conditions.

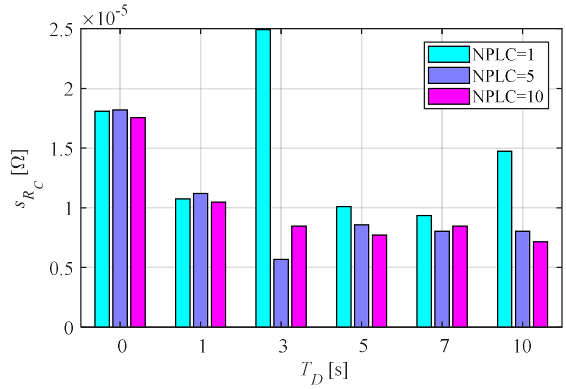

Fig. 6.Standard deviation of sensor resistance in different test conditions.

Focusing on the standard deviation of R_S, it can be highlighted that when NPLC=1 is considered, the overall uncertainty is much higher than those with NPLC=5 and

10 setting (approximatively the double). When no T_D is considered, a higher value of standard deviation is noted. Therefore, it can be state that best trade-off between measurement time and uncertainty is obtained for NPLC=5, as expected also from the datasheet of the instrument [6]. By moving to the sensor resistance R_C, higher values of standard deviation in all the cases are recorded but the same trend is highlighted.

So, for each T_D, best results are achieved with NPLC=5. In fact, passing to NPLC=10, namely doubling the observation time, no considerable improvements in terms of standard deviation are achieved.

Focusing on data for NPLC=5, it necessary to check if measurements of resistances have been performed in steady state condition for each T_D. For this reason, measurements of the resistances have been reported in Fig. 7 and Fig. 8 for the standard and the sensor resistances respectively.

Focusing on the standard resistance R_S, it can be highlighted that when no delay is set, there is a transient effect that last about 10 measurement points. By increasing T_D, this transient effect is mitigated. On the other hands, considering the sensor resistance R_C, this behavior is more evident: at least T_D =3s has to be considered for neglecting the transient effects. Differences on the dynamic behavior can be attributed to different impedance of two channels.

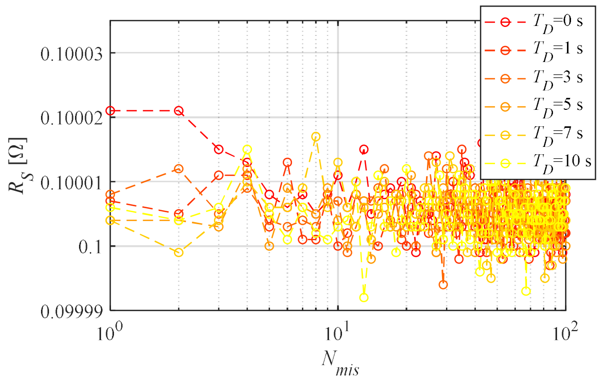

Fig. 7.Measurements of R_S for NPLC=5 and different T_D.

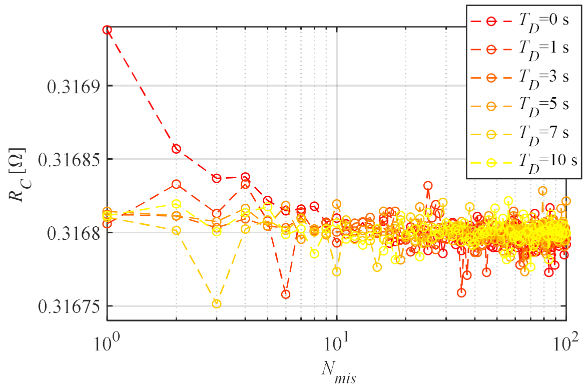

Fig. 8.Measurements of R_C for NPLC=5 and different T_D.

Finally, it possible to declared that the best trade off in terms of accuracy and time is achieved with T_D=5s and NPLC=5; in these conditions the standard deviation on the standard measurement reaches a value of $3.7{\cdot}10^{-6}$ Ω while for the sensor resistance reaches a value of $8.7{\cdot}10^{-6}$ Ω. This difference can be attributed to the design of the PCB sensor and other environmental noise sources.

V. CONCLUSION

In this paper, the metrological characterization of a system allowing to monitor the corrosion of metals has been presented. In particular, a sensor allowing to track the corrosion evolution of pre-corroded of work of art has been presented. The measuring system is characterized by flexibility, modularity, low cost and it allows to perform measurements simultaneously on up to 13 sensors. The system is very promising and will allow to optimize a corrosion sensor for heritage preservation able to take into account the initial state of corrosion of the piece of art under investigation. In the final paper measurement on pre-corroded sensors will be reported.

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