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A portable and autonomous system for the diagnosis of the structural health of cultural heritage (PICUS)

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***Abstract* – An innovative system has been developed, named PICUS (the 'woodpecker' in Latin), and inspired by the auscultation method carried out by the experts in the field of conservation of cultural heritage. This device tapping the surface, controlling, acquiring and measuring some relevant parameters. In a nutshell, it performs an analysis similar to that carried out by a professional who performs a routine examination on the detachments by hand. The experimental apparatus consists of a probe made of an electromechanical percussion element that gently taps the surface producing a sound, an accelerometer to measure the impact force, and a microphone, all connected with an Arduino-like low-cost board, to record and elaborate sounds and the force sensor signal. The probe XY position on the scene is recognized using a low-cost IR camera positioned in the probe and an IR source opportunely positioned outside.**

I. INTRODUCTION

Detecting the presence, the position and the extension of the defects in cultural heritage artifacts is at the base of the analysis of the state of conservation of ancient structures. Non-destructive investigations used in laboratory to find detachments are hardly executable in situ for several reasons: often it is not possible to install complex equipment due to space problems, other times it is not possible to take advantage of the technological infrastructure, connection to the power grid or Ethernet network. For this reason, traditionally, conservators rely on the technique of auscultation, which entails gently knocking with the hand, and listening to the sound produced by the surface. The results of these examinations are translated into the graphic documentation of the discontinuities of the structural elements, detachments and cracks between layers, in order to achieve the conservative diagnosis and outline a project of intervention. Analysis carried out with such method are accurate, but introduces a strong subjective conservator's connotation, which makes it not repeatable. For these motivations, we introduced an automatic system to detect and measure the detachments, and more in general non visible defects. We used a probe that using a cross-correlation algorithm for the measurements made, allows us to detect the detachment phenomena between layers and discontinuity. The proposed technique allows measuring entire surfaces, using a sound correlation method between an acoustic "snap" of the point of interest and an acoustic "reference snap" of a point certainly known.

For this purpose, we have developed a handheld "tester" (Fig. 1), easy to use, safe for the delicate structures to be examined, with a good repeatability of the measurement. The proposed method was implemented in an easy-to-use and inexpensive portable version using an Arduino-like board making the new system suitable for "in situ" operation. It can be also used for monitoring the evolution of the conservative scenario.

Some solutions to the problem mentioned earlier are given in the literature. The most promising methodologies are the non-invasive investigations based on the extent of the cover's surface vibrations, using different techniques both to excite surfaces, and to measure a signal of interest [1-5]. Our method is based on the technique used by professional restorers. They slightly tap the surface under examination with the knuckles of the fingers, and mentally perform a kind of correlation between the sound signals respectively of a point that they judge in good condition compared to another that may not be. This type of analysis, how it's simple to guess, depends heavily on the restorer performing the measurement. When large areas are examined, usually many restorers are engaged, who each examine a part of the artwork. These differences in the total analysis of the surface are difficult to recognize and therefore can lead to errors in the actual diagnosis of the conservation status of the cultural heritage. The system we have developed seeks to fill a gap in the equipment sector linked to this type of analysis, also allowing it to be used

Fig. 1 The PICUS device without the outer protective covers in order to observe the composition of the system interior.

easily in situ, in such a way as to complement the experience of the restorer, confirming or modifying the feeling that each exhibits with respect to the defect measured only with the hand. In this paper we will show the probe, equipped with a microphone that allows the capture of the audio signal generated by the impact of the tapping device on the surface under examination. The audio signal is captured using a low-cost microcontroller electronics unit, and the calculated measurement is stored in a local mass-memory (Fishino Piranha board [6]). In addition, because the probe's position on the measurement scenario is an important parameter that contributes to the correct measurement of the object, a two-dimensional measurement system based on the use of an IR camera (PAJ7025R3, Pixart Inc.) placed in the probe detects the location of an IR source with a large emission's angle that is conveniently placed a few meters away from the surface to be measured, at a distance that covers the entire possible range covered by the camera, which has a fairly wide angle of view. The IR source is independent (battery-powered) and driven by a high efficiency LED driver: this constant current driver is designed to drive high power LED and provides the highest possible efficiency, as this architecture has no switching losses present in traditional charge pumps or inductive boost circuits. The camera sends the X and Y coordinates of the probe to the same microcontroller unit using a SPI protocol, to provide the localization of its position on the plane (Fig. 2). Finally, we will present the results obtained on some laboratory-produced test-objects, to test the goodness of the system and how the information is represented.

II. MATERIALS AND METHODS

Given the vastness of the artistic heritage and the impossibility, sometimes, to perform tests and diagnoses

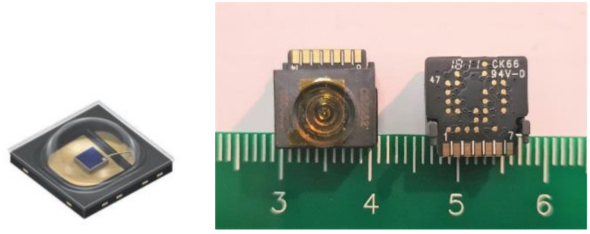

Fig. 2 The two-dimensional tracking system is based on the use of an IR camera (on the right) placed in the probe and an outside IR source (on the left).

in the laboratory or to transport expensive and fragile equipment in situ, together with the prohibitive costs that this type of analysis usually entails, the availability of a pocket-sized system that performs a detachments analysis seems to be a practical solution to solve the problem that arises to restorers, that often have to work in precarious situations and with unconventional and standard tools, relying heavily on their professionalism and experience to conduct a diagnosis that later includes an intervention plan. In this section we will describe the individual components of the system, as well as the algorithm implemented in the microcontroller unit.

A. Tapping device

The device consists of a very low cost solenoid which is the essential part of the hitting device. Solenoids are a good way to induce linear motion for pushing or pulling. This small solenoid is designed to work directly with a low voltage (9 V). The solenoid is positioned on a mechanical system equipped with a mechanical slide with the possibility of calibrating the impact force on the surface to be analyzed depending on the material of the surface, by raising or lowering the solenoid, so as to adapt the hitting device to different materials. You can see in fig. 1 the yellow ring nut that allows you to move the position of the solenoid over a stroke of more than 5 mm. After this calibration, the force exerted by the solenoid is not dependent by the operator: the operator can only place the sensor in a specific point or randomly. The sensor is driven electronically and the force exerted is defined by the hardware that manages the current flowing in the solenoid, which acts as an actuator. The device is then complemented, on the end opposite the one striking the material, by a piezoelectric accelerometer (805M1-0200-02 by TE connectivity) with 200g sensitivity (10 mV/g) up to 12 kHz of bandwidth. It incorporates a stable piezo-ceramic crystal with low power electronics in a shielded housing for stud mounting in a TO-5 case.

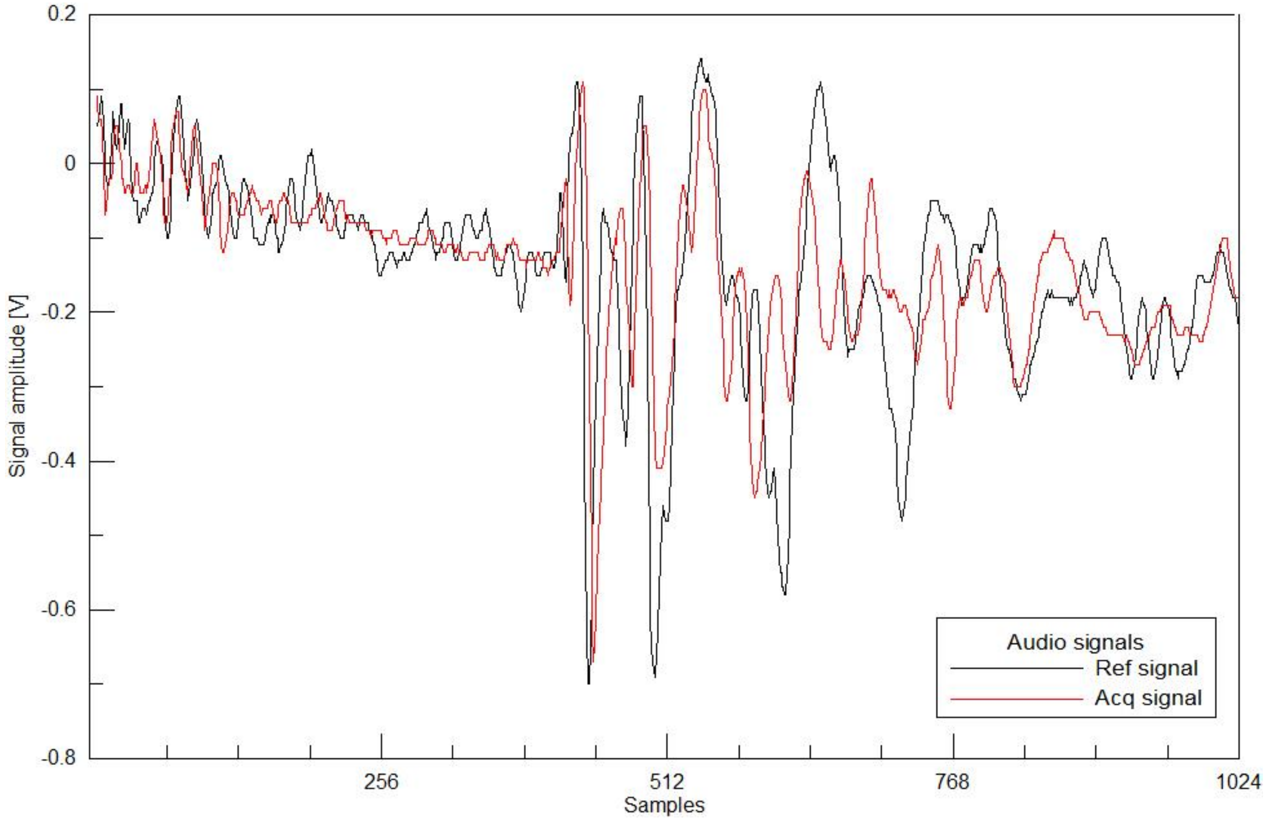

Fig. 3 An example of audio signals acquired by the system: in black the reference signal and in red a signal with a good cross-correlation index.

B. Positioning and tracking system

As mentioned, the position acquisition and tracking system is based on the use of the new PAJ7025R3 sensor from Pixart Imaging Inc (fig. 2). This device is a Multiple Object Tracking (MOT) module that integrates a high-quality CMOS image sensor, image processor, and digital signal processor (DSP). Once the grayscale image is acquired, the PAJ7025R3 immediately processes it and produces relevant output information. The output information consists of the object area, object center coordinates, 4-way object boundary, average/maximum object brightness, object radius, object range, and aspect ratio. The module is developed with advanced algorithms that can dynamically track up to 16 IR-emitting target objects, and return their relative data for further exploitation. The communication interface is through SPI. The tracking objects could be supported through a direct Infra-Red (IR) light source or indirect with passive IR reflector light source. The maximum sensitivity of the module is between 800 and 900 nm, while the remaining lighting spectrum is filtered. The angle of view is 111.3 degree both on vertical and on horizontal (140 degree in diagonal). The focal length is 0.378 mm and the F# is 2.93. The module support programmable exposure-gain control and adopts global shutter scanning mode to achieve great real-time motion tracking results. In addition to a high 200fps frame rate, the module's IR detection mechanism promotes accurate tracking under all ambient light conditions, allowing the module to fully perform in both indoor and outdoor applications.

The system is complemented by an Infra-Red source placed at some distance from the PAJ7025R3 sensor, consisting of a power IR LED diode (SFH4714A) driven by the battery-powered MIC4801 device. The diode has the peak emissivity at 860 nm and an emission angle of about 150 degrees. In this way, the source can be placed in the most convenient position and at the most appropriate distance in order to uniformly cover the surface to be measured. A procedure (an audible beep) is available in the PICUS that makes it possible to know in advance the maximum measurable surface area and then to operate the positioning of the IR source accordingly.

Pixart assures that the module can work properly up to a distance of about 3 meters from the IR source. With the viewing angles of both the module and the IR source, this specification translates into the ability to map (on 4096x4096 points) an area of more than 8 meters on a side, which for the application described here is more than sufficient.

C. Acquiring and Elaboration Unit

The microcontroller board used as the acquisition, control

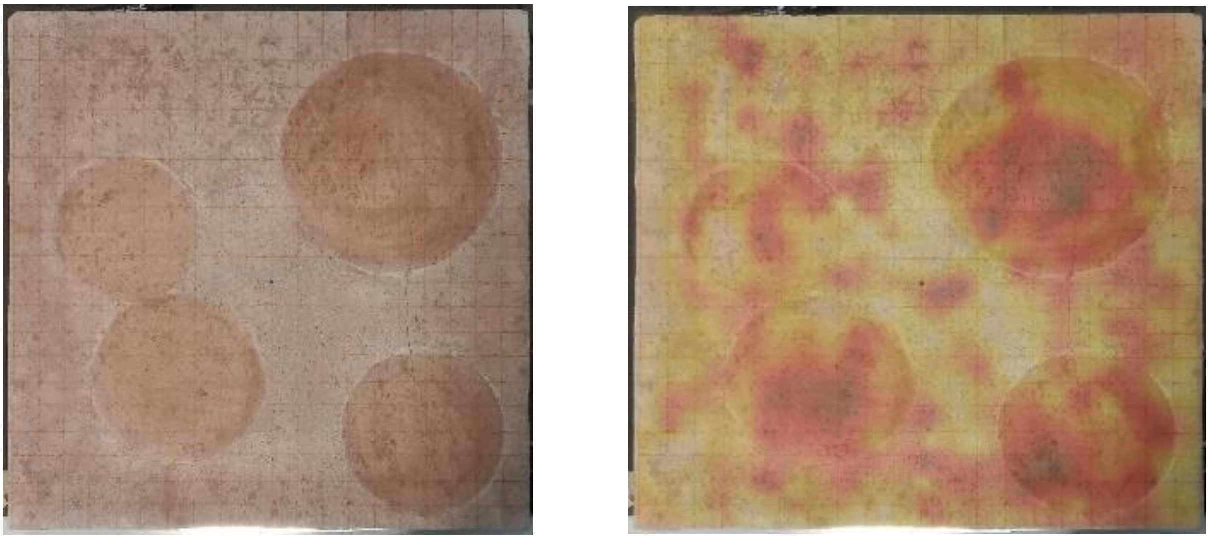

Fig. 4 Measurement made on a laboratory model by assigning false colors to the cross-correlation index

and calculation unit is based on a 32-bit PIC32MX (Microchip Technology Inc., Chandler, Arizona, USA) architecture (120 MHz/150 DMIPS), inserted in an Arduino platform, maintaining its simplicity of use but enormously increasing its potential thanks to the 32-bit micro-controller and additional components. The strengths of the board (called "Piranha", designed by dr. M. Del Fedele [6]) are the possibility of being powered by a LiPo battery, integrates a flash memory of 512 KB which, combined with a RAM of 128 KB, and an A/D (analog to digital) converter 10-bit 1 Msps rate, al-lows the development of extremely complex applications. On the board (60x25 mm) there are also a Wi-Fi module, a slot for microSD, and a Real Time Clock and Calendar.

A shield board, developed ad hoc, is positioned under the Piranha board containing the few hardware components to correctly interface the signals coming from/to sensors (accelerometer, IR camera, OLED display) and to produce the signals necessary to correctly actuate the solenoid (using a step-up converter) and all the necessary driver.

D. Algorithm implemented

The implemented software is based on a cross-correlation algorithm. The audio sampling frequency was set to 48 kHz, and considering that the analyzed signals are in the band up to 6 kHz, the signal is oversampled, in order to avoid aliasing problems. The depth of quantization is 10 bit. As already stated in the introduction, the concept underlying the algorithm is to establish a test point at which there is certainty: this point can, for example, be adherent with certainty. The restorer, based on his experience and professionalism, establishes the test point; with respect to this point all the other points will be compared and cross-correlate, and the result will tell if the point under examination is similar to the one taken as test-point or is definitely dissimilar from it, using the information coming from the correlation index that is calculated by comparing the audio recorded by the test point and the point being measured. The number of audio samples is set to 1024 which is a good compromise between the memory occupation and the fidelity of the recorded signal. The data frame is 21.3 ms long.

Figure 3 shows an acquisition of audio signals obtained hitting the surface first to obtain the reference signal and then to obtain a measurement by a unknown point: the calculation of the cross-correlation vector (2048 samples), the maximum of which represents the index of cross-correlation measured by the instrument, was implemented using a procedure very similar to that used by the commercial software Matlab (MathWorks, Natick, MA, USA), in this case produced a high (> 0.7) cross-correlation index.

III. RESULTS

In Figure 4 we show the measurement carried out on a laboratory test object using the cross-correlation index starting by the audio data. This test object was made using a terracotta tile of 50x50 cm by side. To achieve circular shaped detachments, mortar cups were preformed, which, once dry, were placed on the substrate and covered by the plaster. Specifically, the mortar, which has the same composition as the plaster, was laid on the forms and reinforced for the preventive purpose of preventing an implosion of the preformed detachments as a result of the laying of subsequent layers. The choice was to make circular-shaped detachments with a diameter of 16.5, 14, 16 and 22 cm and a maximum depth of 17, 12, 10 and 18 mm, respectively. The plaster has a thickness of 3 cm and is composed of hydraulic lime, pozzolan and river sand. The plaster has the same composition but has a thickness of 1 cm and a finer grain. Finally, the surface was etched and frescoed with "burnt sienna" to make visible the mapping of previously made defects. The ultimate goal was to assess whether or not the probe is abrasive to the painted surfaces. The Ref point was chosen certainly adherent (in fig. 4 is about in the center of the tile), and used as a reference point for the entire measurement of the object. The data were then processed using the surface map technique by the graphical software Surfer, and the recognition of the four pseudo-circular areas is evident. Only the circle on the upside left is not well defined, probably because an abnormal filling was introduced in this area during the fabrication. The restorer, using the classic method of “knocking” carried out with the knuckles of the hand, confirmed the presence of the defect but obviously without the precision of the method described so far. The presence of isolated points in the analysis of the detachments cannot be confirmed by the restorer’s verification, not only because they are too small to be appreciated with the classic method of knocking, but they could also be false positives. In our experience, only homogeneous areas of defects can be considered as real defects, while nothing can be said about isolated points, which could also be due to measurement errors.

IV. CONCLUSIONS

A low-cost portable device capable of measuring detachments and delamination to help conservators in analyzing the state of conservation of an artefact has been designed. Tests were performed on several test objects to simulate various usage scenarios. All these tests confirmed the validity of the system and its flexibility in use in situ. A wider series of measurements on additional samples, both real and laboratory, is needed to accurately establish the correctness of the measurements. We believe that a qualitative analysis of the surface to be analyzed is sufficient, but further verification of the measurement can be achieved by integrating other measurement techniques besides the cross-correlation. A true “fusion” between measurements made by different methods will allow us to confirm the measurements made in a timely manner so that they are congruent with the manual techniques in use today by restorers.

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