DIGITAL IMAGE CORRELATION IN ASSESSING STRUCTURED-LIGHT 3D SCANNER'S GANTRY STABILITY: PERFORMING DAVID'S (MICHELANGELO) HIGH-ACCURACY 3D SURVEY.

Francesco Mugnai[1]*, Grazia Tucci[1], Andrea Da Re[2]

1DICEA - Dept. of Civil and Environmental Engineering, University of Florence, Via di S. Marta 3, 50139 - Florence, Italy – (francesco.mugnai, grazia.tucci)@unifi.it
2HVK Srl - Consulenze metrologiche, C.so Matteotti, 32A 10121-Torino-TO-ITALY - a.dare@hvk.to.it

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ABSTRACT:

The paper presents results from applying Digital Image Correlation (DIC) technique to determine deformations and verify stability on a gantry during surveying operations on the Michelangelo's David at the *Galleria dell'Accademia di Firenze* museum in Florence. An advanced hi-resolution Structured-light 3D scanner has been used to create a hi-detailed digital twin of the masterpiece. Considering the high scanner sensitivity, a contactless, remote and passive monitoring system of the gantry stability has been chosen to guarantee maximum freedom of movement around the David and avoid any interference during scanning operations. Due to the remarkable elevation of the statue, which reaches almost 7 meters on his pedestal, and considering the cramped operating area around the statue, an ad-hoc gantry has been designed and deployed. The sophisticated scanner's technique and the extreme hi-resolution required for the survey needed firm gantry stability during scanning operations from one side. The complex geometries and the considerable extension of the statue surface impose extended flexibility and a nimble elevation platform from the other side. Thanks to the DIC technique the gantry stability has been constantly monitored with an accuracy of 0.03 ÷ 0,04 pixels, optimising scanning scheduling and, consequently, operations efficiency. A comparison of scans with post-processed deformation patterns allowed to optimise the scanning schedule, minimising downtime, and maintaining the needed platform stability threshold for effective scanning.

1. INTRODUCTION

Michelangelo Buonarroti's David is one of the most famous masterpieces globally, and it is universally recognised as the Florentine Renaissance icon. Thanks to his significance and cultural heritage value, David has been chosen to represent Italy at the Expo 2020 Dubai. Under the hegira of the Ministry of Cultural Heritage and Tourism and the Italian Commissariat for Expo 2020 Dubai, the masterpiece will have its double and will be the most faithful version ever produced (Italian General Commissioner's Office for Expo DUBAI 2020). The development of accurate and cost affordable 3D surveying techniques and instruments has permitted in recent years to extend the use of the most cutting-edge technologies and methods to architectural, environmental and Cultural Heritage fields. In this particular case, the 3D survey has been performed Using a Structured-light 3D scanner from Hexagon Manufacturing Intelligence, the StereoScan neo (Hexagon Manufacturing Intelligence, 2020). The instrument has been developed for automotive industries, but considering his performances and technical specs, such as an accuracy in the order of microns, has been exploited to create the David's digital twin[1]. The obtained 3D model has been then used to realize a real-size 3D print of the statue.
In 1998, a Stanford University and Washington University jointed research team, headed by Prof. Marc Levoy, carried out a scanning campaign of the statue with a resolution of 0,29 mm and a dynamic range of 20.000:1 (Levoy et al., 2000).

At the beginning of 2000's, image processing methods and techniques have been designed and improved their effectiveness in parallel with the progress of algorithms, computing power and sensors (Chen et al., 2017; Hild & Roux, 2006; Wahbeh et al., 2003; Wen et al., 2021).
Digital image processing can be considered one of the most innovative branches among remote sensing techniques and can identify and detect a structure's surface changes (Wen et al., 2021). In recent years, different image-based approaches for displacement monitoring schemes have been proposed (Bruno et al., 2020; Buckner, 1983; Caporossi et al., 2018; Debella-Gilo & Kääb, 2011; Ehrhart & Lienhart, 2015; Leprince et al., 2007). Digital image processing can be an essential tool for monitoring purposes. Generally, the Digital Image Correlation (DIC) technique, which is an optical-numerical measurement technique, can provide full-field 2D-displacements of any type of object's surface (Bing Pan et al., 2008; Sutton et al., 2009).
Some authors have used ground-based optical cameras, and video-cameras, for structural monitoring purposes thanks to high-quality performances (Chen et al., 2017; Farquharson et al., 2015; James et al., 2006; Travelletti et al., 2012). Some algorithms and software, e.g IRIS developed by Nhazca (Hermle et al., 2021) or the Digital Image Correlation routine (Tertius Bickel et al., n.d.) have been developed.
Digital Image Correlation through PhotoMonitoring™ techniques (Antonielli, B., Caporossi, P., Mazzanti, P., Moretto, S., & Rocca, 2018; B Pan et al., 2013; Vandenberg, 1992) has been applied to verify gantry stability. The used gantry (Figure 1a, 1b) is an ad-hoc elevator with a pneumatic system movement to increase or decrease the elevation of the plane support that hold the Structured light Scanner.

[1] For copyright reasons, images or other elements of the David's statue Digital Twin cannot be published.

* Corresponding author

Digital Image Correlation is an optical-numerical remote sensing technique that offers excellent opportunities to measure displacements and / or deformations on the surface of the monitored object, both in 2D and 3D (Bickel et al., 2018; Lava et al., 2010; Mesas-Carrascosa et al., 2014).
The accuracy in the measurement of displacements achievable with the DIC technique is strictly dependent on the type of sensor used (type of camera, size, quality and resolution of the sensor, photographic lens, etc.) and on the distance between the camera and the scenario being monitored. In the application field, the DIC technique allows to monitor, in a spatially continuous and automatic way, the sectors of the scenario characterized by deformation processes in progress, providing a quantitative estimate about the rates and trends of displacement.

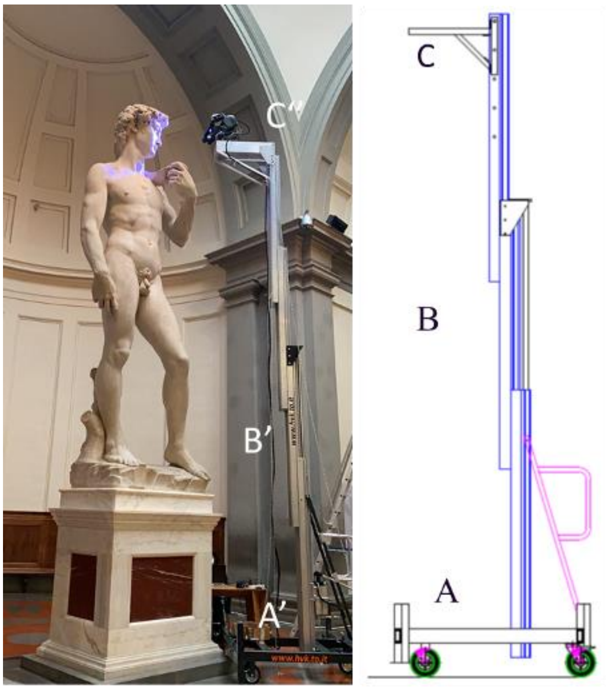

Figure 1: Surveying of David at the Galleria dell’Accademia museum in Florence: on the left, the ad-hoc gantry, made and optimized by 2HVK sr. for scanning operations performed in 2020. On the right, the ad-hoc grant scheme (A-A’) platform, grant main structure (B-B’) scan’s support (C-C’)

2. MATERIAL AND METHODS

For stability monitoring of the gantry and the DAVID statue, two different systems has been used, a Terrestrial TInSAR (Terrestrial Interferometric Synthetic Aperture Radar) and an optical video camera.
Each of the systems have been used to check both the statue and the gantry and a good correspondence between results of the two different system can be here disclose, however in this paper, the optical video system’s results have been only presented. The gantry is composed by a platform (Fig.1-A), a main central body that can be lifted or lowered thanks to a manual hydraulic actuator (Fig.1-B) and a support for Anchoring cameras, Scanners, or other sensors on the top (Fig.1-C).

2.1 Optical Video survey system

The used optical video camera has been the Canon Legria HF G30 camera, with the HD CMOS Pro advanced 1/2,84.
The camera, which is fixed on an heavy duty stable tripod, has been positioned allowing to records compound displacements in x, y, z axis of the gantry and the David statue.

Figure 2: Canon Legria HF G30 camera, deployed to perform 60fps images acquisition for monitoring gantry stability and deformation.

Considering the distance between the photographic sensors and the scenario (forklift), the size and resolution of the sensor as well as the focal length of the lens, it is possible to obtain the Ground Sampling Distance (GSD) or the size of a pixel on the ground. Taking into account the technical specifications of the installed system and the monitoring scheme, it was possible to obtain the GSD value for the system installed at the Galleria dell'Accademia in Florence, in a range between 6 ÷ 7 mm (gantry).

Figure 3: Camera installed on a trypod looking at the David statue and Gantry.

2.2 Digital Image Correlation analysis

DIC analysis have been performed through the use of IRIS software, developed by Nhazca S.r.l. start-up Sapienza. The software allows for Change Detection (CD) and Digital Image Correlation (DIC) analysis by analysing the data acquired from different platforms and sensors. DIC processing can be performed between two different images representing the same scene acquire at different time one from each other, or on a stack of images from which time series of displacement can be obtained.
The analyses on the David were carried out using the Phase Correlation (PC) algorithm (Tong et al., 2019) which is based on a representation in the frequency domain of the data, usually calculated through fast Fourier transformations (Fig. 4), with a 32 pixel floating window.

$$\begin{aligned} \mathrm{PC} &= F^{-1}(Q(u,v)) = F^{-1}\{\exp(-i(u\Delta x + v\Delta y))\} \\ &= \delta(x-\Delta x, y-\Delta y). \end{aligned} \quad (1)$$

In this way the reconstruction of deformation or deformation pattern has been performed and even subpixel accuracy can be obtained (Lin & Lan, 2010; Ma et al., 2018; B Pan et al., 2013).

Figure 4 presents results of DIC elaboration on the David's statue. A deformation map is superimposed to the 2D picture of the David statue and the gantry. The colour bar on the right shows the deformation value identified through the application of the DIC algorithm. Green colour represents areas with no deformations, Blue colour represents maximum deformation. Looking at the gantry's s main vertical section, some Blue zones can be identified on elevation stem and in the surrounding area. This noisy behaviour is a result of moving elements such as power cords, data cables and retention chains, that float during frames acquisition.
Some coloured pixels are noticeable even in the right part of David's breast and chick; in this case the wrong Phase Correlation results came from marble's lighting changing. In correspondence of some peculiar surface concave curved geometries the light coming from roof windows induce some surface chromatic shift that are interpreted from PC algorithm as pixel changing. In order to analyse gantry and David recorded deformations 3 reference areas have been identified: one in the upper part of the gantry's Scanner support, and one on the scanner's body and one is in correspondence of the right statue's chick (Fig. 5, 6, 7, 8).

Figure 4: Superimposition of DIC analysis's results on 2D picture of David statue.

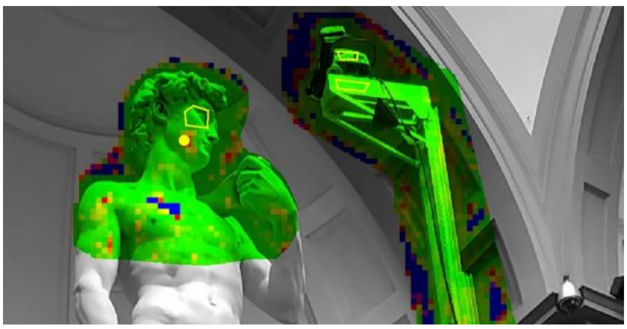

Figure 5: Reference area on the statue and gantry's top for deformation analysis: Overall view.

Figure 6: Reference area on the Scanner support for deformation analysis: Yellow outlined area on the Scanner support.

Figure 7: Reference areas on the Scanner body for deformation analysis: Yellow outlined area on the scanner's body.

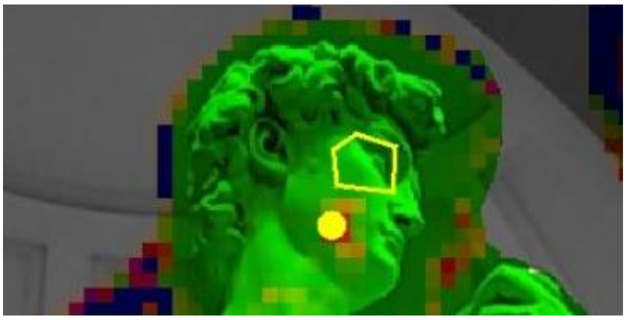

Figure 8 - Reference area on the statue head for deformation analysis: Yellow outlined area on the right David's chick.

3. RESULTS AND DISCUSSION

Exploiting IRIS software's exporting features, which allow to save a text file with DIC elaboration results[2], a chart for each analysed portion on the statue and gantry has been generated. In the X axes progressive frames number is reported, in Y axis measured displacement expressed in pixels is reported. As mentioned above, the acquisition campaign has been conducted maintaining a constant frame rate of 60 frames per second on the camera settings. This results on a minimum time step of 0,016 seconds. Each chart comprises a time span of 15 seconds. The duration has been decided hypnotizing a substantial disposition of the gantry to a stable behaviour. Looking at the gantry's chart (Fig.11), line's trend after frame 500 can be interpreted as a substantial stability. Indeed, after an initial perturbating pulse, generated by the movement for increasing or decreasing gantry's elevation (the moving system is a manual pneumatic actuator) which impose to the gantry's body an oscillating movement. In the chart in figure 9, but also in the other charts this is well appreciable as a saw teeth shape. The oscillation has an almost constant period of 46 frames (0,76 s), however, the amplitude presents a damping behaviour up to a constant value of +/- 0,03 pixels, under the instrumental

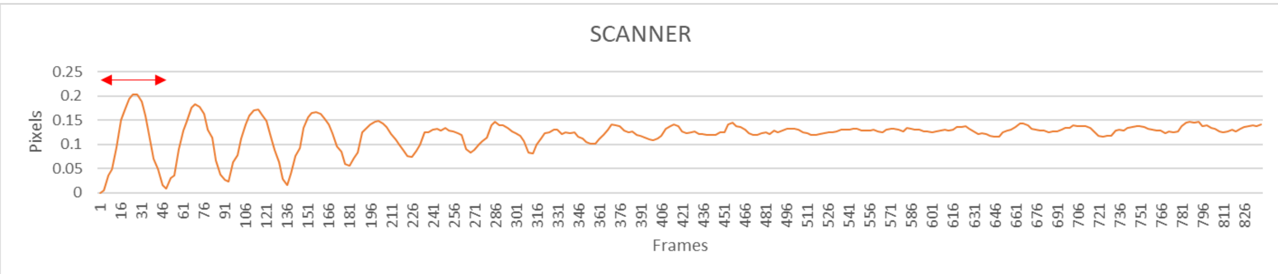

Figure 9 – DIC analysis's results on Scanner body.

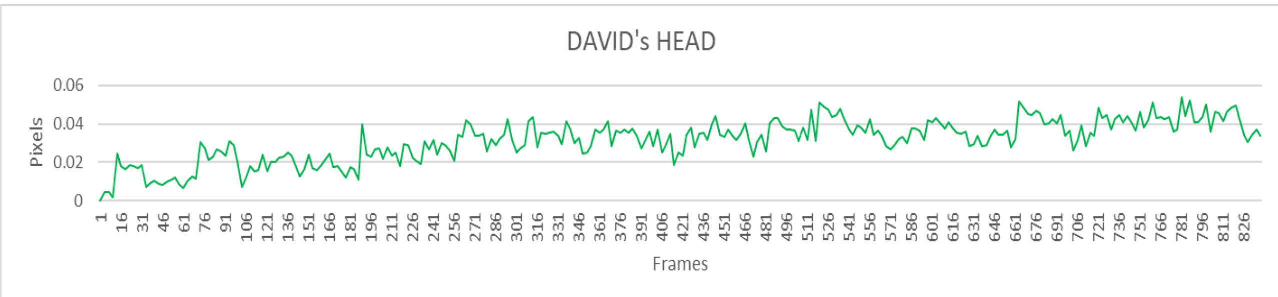

Figure 10 – DIC analysis's results on the David's Head (Chick).

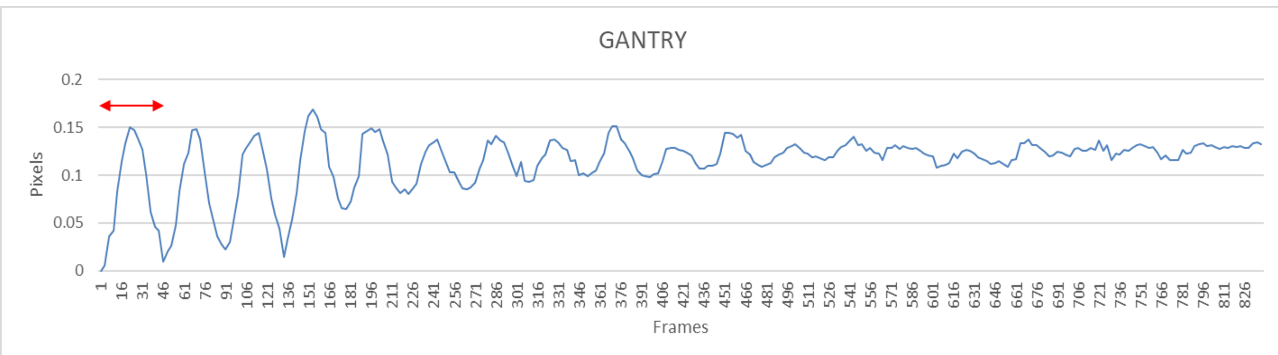

Figure 11 – DIC analysis' results on the gantry's Scanner support.

[2] In case of using geo-referenced pictures/otophotos/ orthomosaics the pixel position information is maintained in the .txt exported file.

sensitiveness threshold. Figure 9, which represent the chart of the DIC analysis' results for the Scanner, shows a very similar behaviour of the Scanner body to the movement imposed by pneumatic actuator. This is not a surprising result, as the Scanner, which is a rigid body, is solidly fixed to the gantry's scanner support.

peaks can be identified at 1.4 Hz (dominant) and 2.8 Hz for Scanner body and gantry. The signal corresponding to David's statue does not show any noticeable oscillating frequency.

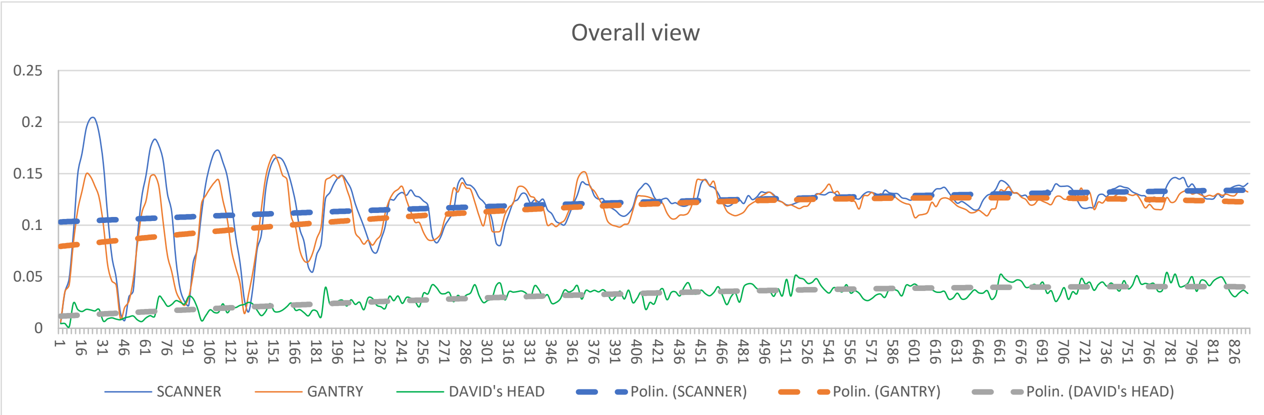

Figure 12 – DIC analysis's results, Overall view and tendency lines.

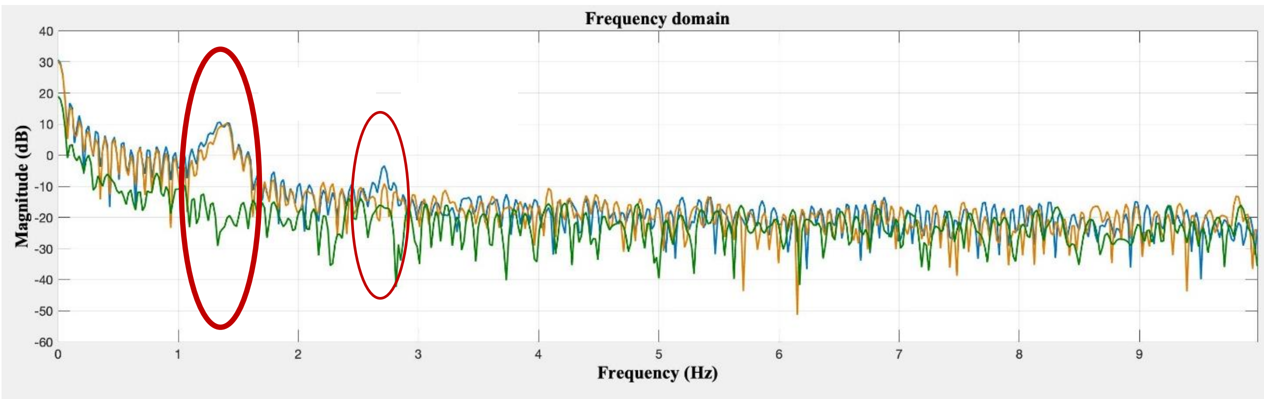

Figure 13 – DIC analysis' results in the frequency domain.

A different situation can be appreciated by looking at figure 10 in which the measurements on the David's head (chick) are reported. Differently from the behaviour recorded for Scanner and gantry's Scanner support, the oscillation amplitude is much smaller. We could even agree on the fact that no oscillating movements can be clearly perceived. The optical system sensitiveness threshold doesn't allow discriminating oscillating component within the analysed signal.

It is even wort to notice that all the three signals present a trend, and the second order polynomial tendency lines are quite similar one to each other.

This similarity, considering that the acquisitions have been made by the same sensor contemporarily, suggests that for some reasons, during the acquisition the instrumentation is affected by some drift. The drift's origin is not clear, however some hypothesis could be: a) The load of the operators could have impose a deformation field on the ground, and indirectly on the camera tripod. b) The camera sensor has some internal drifting process that affects the acquisitions. c) Both the statue and the gantry experienced a similar deformation pattern due to ground characteristics. Even if the first or second hypothesis are the more reasonable ones, as after 500 frames, that correspond to about 8.3 seconds, the signal noise amplitude is higher than the deformation's amplitude, the performed measurements do not allow for accurate evaluations.

Lastly, extracting main signal's oscillating frequencies analysing data in the frequency domain (Fig. 13), two main

4. CONCLUSIONS

This paper presents some of the technical setups and arrangements that maintain accuracy of 0.029 mm, one order of magnitude lower than Levoy's work. Maintaining a dynamic range[3] of more than 200.000:1 (Feng et al., 2018; Scott et al., 2001), scanning a complex and fragile surface like David's one, in a sensitive and narrow space like the exhibition museum venue, requires some ad hoc designed technical solutions, other than an extremely advanced scanner. One of these technical solutions that plays a crucial role in maintaining a considerable dynamic range is a robust, rigid and stable scanner platform that guarantees a flexible and finely adjustable design and a strong and reliable stability on its entire elevation at the same time. The used Scanner has its own stability sensor, which guarantee that the acquisition is performed under a certain stability threshold. A further tool to check stability, as proposed in this work, could be considered as an unjustifiable redundancy. However, considering the very short time window (15 days) available to perform the entire survey, having a reliable information on the behaviour of the statue and the gantry, in terms of oscillations and stability, allows to make a more effective planning reducing pauses and downtimes. In this way, the deployed hi-resolution scanner can work at its maximum

capability and performances for the entire surface and statue elevation.
It is also wort to notice that the Accademia Museum is open to the public for the whole year, and setting up a survey during opening hours is forbidden and unfeasible for logistic reasons. Performing the surveying activities during the night only, would have been also impossible, considering the complexity of the general instrumental setup and the very sensitive context. This surveying activity was only possible thanks to the closing period generated by the covid emergency. One shot opportunity. Furthermore, recording overall displacement of the surveyed subjects, David and Gantry, would allow to implement a correction procedure for mitigating an eventual stability sensor misfunctioning.

AUTHOR CONTRIBUTIONS

Conceptualisation, Francesco Mugnai, Grazia Tucci; methodology, Francesco Mugnai; software, Francesco Mugnai; validation, Francesco Mugnai; formal analysis, Francesco Mugnai; investigation, Francesco Mugnai, Grazia Tucci; resources, Grazia Tucci, Andrea Da Re; data curation, Francesco Mugnai ; writing—original draft preparation, Francesco Mugnai, Andrea Da Re ; writing—review and editing, Francesco Mugnai, Grazia Tucci; visualisation, Francesco Mugnai; supervision, Grazia Tucci; project administration, Grazia Tucci; funding acquisition, Grazia Tucci. All authors have read and agreed to the published version of the manuscript.

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